THE ORIGIN OF CONTINENTS AND OCEAN BASINS

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This book deals with the origin, structure, and tectonic behavior of the earth's crust beneath continents and oceans and describes principal stages of the earth's geologic history. The author attaches much importance to geosynclinal cycles and their role in continental crust build-up and discusses intriguing hypotheses explaining the presentday face of our planet.

THE ORIGIN OF CONTINENTS AND OCEAN BASINS

ИЗДАТЕЛЬСТВО • МИР •

М. В. Муратов

ПРОИСХОЖДЕНИЕ МАТЕРИКОВ И ОКЕАНИЧЕСКИХ ВПАДИН

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Preface

The territory of the Soviet Union, which extends from the Carpathians and the Baltic Sea on the west to the Pacific Ocean on the east, is geologically very complex. It is extremely rich in mineral materials, such as ores of ferrous and non-ferrous metals, fossil coal, oil and gas, building materials, and subsurface water. Although these are widely used by Soviet industry and agriculture, large mineral resources are still concealed deep within the earth's crust waiting to be discovered by skilful drilling.

To efficiently forecast and locate new mineral deposits, we must know their modes of occurrence and distribution patterns and have a general idea of the earth's internal structure and the ways the various parts of the earth's crust have developed into the complex entities containing mineral materials.

The differences between the various parts of the earth's crust are due to their distinct geologic histories which can be understood by thoroughly studying the constituent rocks and the relationships between sedimentary formations, intrusive bodies, volcanic rocks, dikes, and veins. In the final analysis, it is the rocks with their mutual relations that provide the primary information enabling the geologist to compile geologic maps and cross-sections of the earth's crust. These, in turn, help decipher the internal structure of the crust and reconstruct in great detail the geologic history of a given area.

To properly understand the structure and history of each particular region, it is necessary to have a thorough knowledge of its relationship with the adjoining parts of the earth's surface and to have a general picture of the processes affecting the entire earth's crust or large parts of it.

The continents and ocean basins are the largest constituent parts of the earth's surface; therefore, their history and evolution are of utmost importance to geology.

The purpose of this book is to familiarize the reader with the present state of the field and to help him in his further studies.

I

STRUCTURE AND AGE OF THE EARTH'S CRUST

FACE OF THE EARTH

When traveling by train or car we can see that the earth's surface is extremely irregular, with high watersheds, hills, deep and wide river valleys, and gorges and ravines. Approaching mountains and gaping at the ragged ridge through the bluish mist, we are filled with awe at the sight of inaccessible rocky peaks and breath-taking cliffs.

If we climb one of the peaks, we are overwhelmed by the beautiful and imposing mountainous landscape and by the magnificent view. We also admire the forces of nature that have raised the range and the peaks so high above the plain or sea.

From an airplane, especially from a modern jet flying at a height of 8 to 10 kilometers, the earth's surface looks smoother, like a printed map, and even the lofty Tien Shan and Caucasus mountains look like low hills.

Imagine yourself on board of a satellite orbiting the earth at a height of hundreds of kilometers; through the haze of the earth's atmosphere and patches of clouds you will see all the irregularities of the earth's surface smoothed out as if on a school globe.

As far back as 200 years ago, the great scientist Mikhail Vasil'evich Lomonosov understood that the continents and ocean basins are the basic elements of the earth's surface. Mountain ranges, valleys, and lakes are no more than tiny specks on the huge bulks of the continents. In *On the Earth's Strata* Lomonosov wrote: "The tallest mountains form entire parts of the world, because the enormous Riphean, Caucasian, Lunar, Atlantic, and Alpine ranges, Cordilleras*, and other mountains are mere hillocks as regards

* The "Riphean Mountains" stand for the Urals, the "Atlantic Mountains" for the Atlas Mountains, and the "Lunar Mountains", perhaps, for the range thought to exist at the head of the Nile, but found to be non-existent in the 19th century.

their height and extent. ... That these parts of the world are mountains in their own right is an indisputable fact, since they have entire world-famous mountains for their summits and the deep and in most cases unfathomable bottom of the sea for their valleys; the sea bottom is by all rights the surface of the earth". He further noted that "the four known parts of the world are the five principal mountains, i.e. all of Asia, Africa, Europe, and South and North America."

The ocean depths were not yet known in Lomonosov's time, but now we know definitely that the mean height of the continents is 840 meters above sea-level, and the mean ocean depth 3 800 meters below sea-level.

The continents consist mainly of plains or relatively low uplands. Likewise, flat plains submerged to depths between 3 000 and 6 000 meters compose 80 percent of the ocean floor. The mountain structures rising over the mean level of the continents form relatively narrow belts grouped into a comparatively small number of systems. Similarly, ocean deeps, called trenches (7 000 to 10 000 meters below sea-level), form a clearly defined system of narrow curved moats; and narrow mid-oceanic ridges and island arcs also occupy limited areas.

Continental slopes are transitional elements between ocean basins and continents. Margins of continents are often covered by shallow seas. These areas are called continental shelves.

Table 1

Areas of the Continents and Ocean Floor

Description	Area, mln sq. km	Percentage of earth's surface
Continents and islands	148.63	29.2
Water surface	361.45	70.8
Earth's surface	510.08	100.0
Eurasia	54.38	10.6
Africa	30.28	5.1
North America	24.23	4.7
South America	17.85	3.5
Australia and Oceania	8.56	1.7
Antarctica	13.33	2.6
Ocean surface	328.44	64.3
Arctic	6.64	1.3
Pacific	164.31	32.2
Indian	70.78	13.8
Atlantic	86.71	17.0
Ocean floor	262.72	51.5
Deep-water seas (Coral, Sea of Japan, Banda, Timor, Celebes, Caribbean, Mediterranean, Black, Arabian, Red, and Greenland)	17.53	3.4
Major shelf seas (South China, Bering, Okhotsk, Arafura, East China, Java, North, Baltic, and Sea of Azov)	15.48	2.9

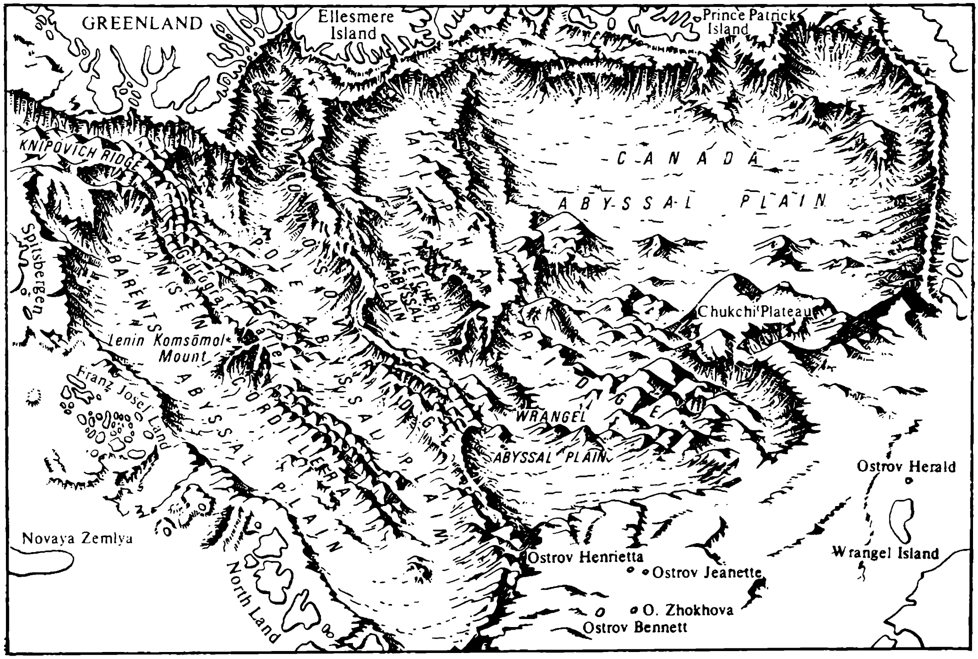


Fig. 1. The surface of the Arctic Ocean floor (after R. M. Demenitskaya, 1967)

Thus, our planet's surface is characterized by two major levels: the prominently elevated continental masses and the flat ocean basins. The latter occupy about 263 million square kilometers, that is, about 51.5 percent of the entire surface of the globe (Table 1).

If we removed all the water from the oceans, say by evaporation, the earth's surface would present quite an unusual picture. The flat plains of the ocean floor would be dominated by huge and on the whole slightly dissected masses of continents topped by high and narrow mountain ranges and volcanic cones, as if two worlds, with different atmospheric pressure (if any at all), climate, flora, and fauna (Fig. 1) co-existed on the earth's surface.

All this is difficult to imagine. The earth has a definite amount of sea water, about 1 370 million cubic kilometers. The water fills entirely the ocean basins and spills over the edges of the continents. The level that the water reaches is called the World Ocean level. It is changeable, depending chiefly on the amount of water, and in the course of the earth's evolution this level has changed considerably, as has the earth's topography. Even in the not-so-distant geological past, in the Quaternary Period, during the Great Glaciation Epoch, large water masses were entrapped in the thick ice cap covering a considerable part of the northern continents and Antarctica. As a result, the level of the oceans dropped appreciably all over the world. After the huge glaciers thawed out, the sea-level rose to its present level, and sometimes even much higher. It is quite probable that during some relatively short time intervals (several tens of thousands of years each) within

the Quaternary, the World Ocean level was at first 20 to 40 meters, or even more, above the present one before and after the Great Glaciation Epoch and then dropped below "normal". Even now if the ice covering Antarctica and Greenland were to thaw, the level of the seas and oceans would rise by 67 meters all over the world.

We have already pointed out that the ocean basins are completely filled with water. If the amount of water decreased so that the ocean level dropped by 1 000 or even 2 000 meters, shelf seas and many underwater uplands would emerge. As a result, the surface area of the oceans would naturally reduce, but their outlines would remain generally the same. Even if the ocean level dropped by 3 000-3 500 meters, which would require halving the existing amount of water on the earth, the outlines of the main oceans—Pacific, Atlantic, and Indian—would hardly change. This indicates that the earth's principal water reservoirs, i.e. ocean basins, are depressions of the earth's surface whose floor is at an entirely different level than the surface of the continents.

Land elevations and sea depths are conventionally measured from the sea-level. This datum, however, not only changes with time, but is altogether accidental, depending upon the amount of water on our planet, which is generally unrelated to the crustal structure. Hence, to properly understand the features and origin of the actual surface of our planet, the face of the earth, we should visualize it without its water cover.

The division of the earth's surface into two main levels—continental and ocean floor—reflecting the profound differences in the structure of the earth's crust under the continents and oceans, stems from the entire history of the earth's crust and the globe, and has no bearing on the amount of water on the earth. These differences spring from the processes occurring deep inside the crust and the mantle.The nature of these processes, which cannot be observed directly, is gradually clarified through geologic, geophysical, and geochemical investigations.

CONTINENTAL AND OCEANIC CRUST OF THE EARTH

In the past few decades a more or less clear picture of the structure of our planet's interior and its shell, the crust, has been obtained by geophysical techniques. Seismologists have made the greatest advances in this field. Earthquake-induced elastic waves propagating through the entire globe are recorded by high-precision seismic instruments; the data obtained are processed by modern calculation methods and supply information on the physical properties of the deep-seated layers constituting the earth.

We know now that the globe consists of three main parts: the earth's crust, 5 to 70 kilometers thick, the mantle, and the core.

The earth's crust is separated from the mantle by a sharply defined interface named the Mohorovičic (or M) discontinuity, after Professor S. Mohorovičič, a seismologist from Zagreb, Yugoslavia, who discovered it in 1914.

The core remains a mystery in many ways. Its surface lies at a depth of 2 900 kilometers and marks a sharp distinction between the physical pro-

perties of the core and the mantle. The core is about 7 000 kilometers in diameter. Despite its high density, the outer zone of the core, extending to a depth of about 4 580 kilometers, resembles a liquid in that it transmits no transverse seismic waves. Then follows a zone of an unknown nature, about 540 kilometers thick, which absorbs seismic waves. Finally, still deeper, lies the solid core of the earth; it is a sphere about 2 500 kilometers in diameter, with properties of a metallic body.

The core is responsible for the earth's magnetic field, whose polarity has repeatedly reversed, that is, the northern and southern magnetic poles have replaced each other, throughout geologic time. This is attributed to the liquid state of the core's outer zone.

The mantle has a complex structure and is subdivided into three layers called the upper (B), middle (C), and lower (D) mantle. We are best informed on the composition and structure of the upper mantle; very little information is available on the middle mantle, and our knowledge of the lower mantle is still highly speculative. Even the nature of the upper mantle remains rather obscure. According to the most widespread concepts, below the M-discontinuity the upper mantle is composed mainly of peridotite, that is, has ultrabasic composition; its density permits the propagation of longitudinal seismic waves with a velocity greater than 8.0 kilometers per second.

Rock fragments, now enclosed in diamond-bearing diatremes and no doubt expelled from the mantle, as well as xenoliths, supply information on the mantle's composition. According to V. S. Sobolev (1970), the topmost upper mantle largely consists of spinel peridotite, while the deeper portions (down to approximately 150 kilometers) consist of garnet (mainly pyrope) peridotite.

It has been recently discovered that at depths of approximately 100 to 150 kilometers, the upper mantle is in a plastic, molten state. This layer is located by seismic techniques; it is of varying thickness, the greatest difference being observed between its sections beneath the continents and oceans.

The plastic layer of the mantle is now considered the source of volcanic products and of volcanism in general. It is called the asthenosphere. The upper mantle above the asthenosphere is solid and, together with the earth's crust, is called the lithosphere, the stony shell of the earth. At the boundary between the solid lithosphere and the plastic asthenosphere we can expect major detachment faults and lateral slipping of lithospheric blocks.

Reflection shooting and gravity surveying of the earth's crust have greatly helped establish its structure, particularly the considerable difference between the crust beneath the continents and oceans (Fig. 2).

The continental crust greatly varies in thickness: it is 30 to 40 kilometers thick beneath plains and 50 to 60 kilometers thick beneath mountain areas and highlands, such as the Caucasus and Tien Shan. Thus, under mountains the earth's crust bulges downwards, producing a kind of a mirror image of the mountains. The resulting downward protrusions are called 'mountain roots'. The crust is especially thick under the Pamirs, the Hindu Kush (more than 60 km), the Himalayas (perhaps 75-80 km), and the Andes (75 km); the highest ranges have the deepest roots. The existence of the roots was established by gravity surveying back in the 19th century (I.D. Lukashevich and others), and this led to the development of the isostasy hypothesis of the

equilibrium between the crustal sections and the substratum. The presence of mountain roots has recently been confirmed by reflection shooting.

It has been found that the continental crust generally consists of three major layers differing in density. The upper layer, 2 to 10 kilometers thick, is composed of the least dense (about 2.2 g/cm^3) sedimentary strata, its longitudinal wave velocities ranging from 1.8 to 5.0 km/s.

The next layer is denser (about 2.4-2.6 g/cm^3). Here, the velocities of longitudinal waves caused by earthquakes or artificial explosions are between

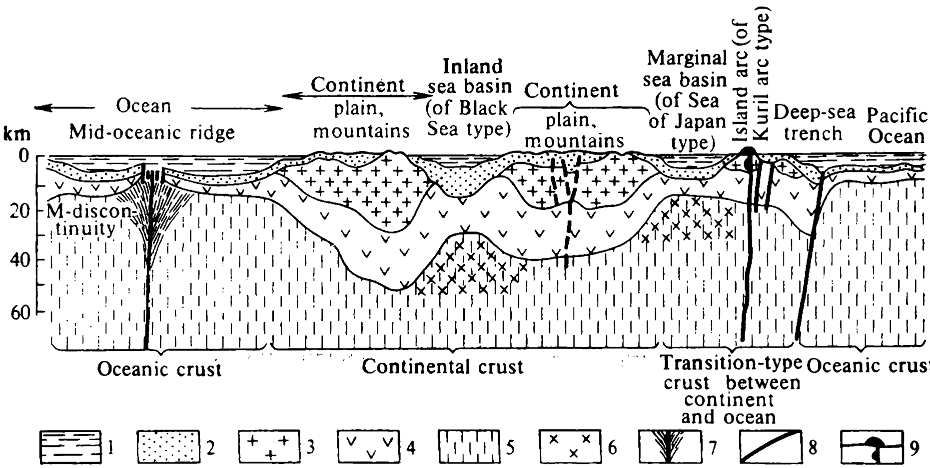


Fig. 2. **The structure of continental and oceanic crust:**

1 — water;
2 — sedimentary rocks;
3 — granitic-metamorphic layer;
4 — basaltic layer;
5 — mantle of earth;
6 — denser part of mantle;
7 — less dense part of mantle (serpentinized rocks?);
8 — deep-seated fault;
9 — volcanic cone and magma chamber and passageway;
M — discontinuity

5.0 and 6.2 km/s. This layer, called granitic-metamorphic or simply granitic, more frequently reaches 10 kilometers and occasionally 20 kilometers in thickness and is made up of granite, gneiss, and other metamorphic and igneous rocks found in the upper continental crust. It is exposed at the surface in many places, such as on the Kola Peninsula, in Karelia, Finland, Sweden, the Ukraine, and the central Caucasus, Urals, Tien Shan, Altai, Sayan, Alps, Carpathians, Rockies, and Cordilleras. In other places on continents, the granitic-metamorphic layer is buried under the sedimentary cover, its depth thus depending on the thickness of this cover.

The lower layer of the continental crust has a density of 2.8 to 3.3 g/cm^3; longitudinal wave velocities are even greater here than in the preceding layer and range from 6.0 to 7.6 km/s. It consists of heavier rocks and is similar to basalt, gabbro, and other basic igneous rocks in density and seismic velocity. Hence it is usually called basaltic, though it is by no means composed entirely of basalt. From geophysical evidence, this layer is 15 to

25 kilometers thick, and even up to 40 kilometers in some places on the continents.

Recently many scientists have suggested that the layer under the continents consists largely of products of profound metamorphism (called granulite facies). These are quartz-feldspathic gneisses containing garnet and pyroxene and plagioclase gneisses containing no mica. Their densities and seismic velocities are precisely the same as those observed in this layer. Hence it is highly probable that granulites do constitute a large part of this layer, but it evidently also contains such basic rocks as gabbro, anorthosite (a special type of feldspathic rocks) and basalt. The layer may thus be called granulitic-basaltic, though it is more frequently called simply basaltic. Charnokites, which are similar to granites in composition, are also included in this layer. But true granites appear to be untypical of this deep part of the crust; they are, however, widespread in the overlying granitic-metamorphic layer, where granitization also takes place (V.V. Beloussov, 1965). As mentioned above, the basaltic layer is sharply separated from the subcrustal material or the earth's mantle by the M-discontinuity. Longitudinal wave velocities in the mantle are even higher, ranging from 7.8 to 8.5 km/s, and the density of the basaltic layer exceeds that of the granulitic-basaltic layer. However, in the deepest parts of the continental crust, between the granulitic-basaltic layer and the mantle, rock masses of intermediate density occur in some places, with longitudinal wave velocities as high as 7.4-7.8 km/s. They are thought to be made up of basaltic layer material with inclusions of denser rocks, most probably eclogites. Eclogite is a pyroxene-garnet rock identical with gabbro and basalt in chemical composition. It differs from them, however, in mineralogic composition (garnets and pyroxenes) and is formed at higher pressures. The density of eclogite is greater than that of gabbro (3.4 to 3.6 g/cm^3 against 2.9 to 3.0 g/cm^3).

Quite a different type of crust underlies the ocean floor. Thinner and containing no granitic layer, it consists only of two main layers, sedimentary, 0.2-0.5 to 3 kilometers thick, and basaltic, 3 to 12 kilometers thick. An interlayer, which is conventionally called the "second layer", can be discerned in some places; it is 1 to 2 kilometers thick, has a somewhat lower density than the basaltic layer, and is thought to be composed of lavas and volcanic tuffs. Hence the total thickness of the melanocratic* crust, which underlies the oceans, is merely 5 to 15 kilometers, increasing to 20 kilometers only near continents and under oceanic islands and underwater ranges. Thus, in the center of the Pacific, the earth's crust is only 5 to 7 kilometers thick.

Within the continental slope bordering the oceans, the oceanic crust passes into the continental crust. The transition is very sharp and is marked by the appearance of the granitic-metamorphic layer and an abrupt thickening of the earth's crust under the continents. The bench of the continental slope, which surrounds the continents and separates them from the ocean basins, is exactly where one type of crust passes into the other as the granitic layer appears in the earth's crust.

* The melanocratic crust is made up of basic rocks rich in dark-colored (melanocratic) minerals, such as pyroxenes, basic plagioclases, and amphiboles.

Shallow-sea areas and shelves are underlain by a continental-type crust. In fact, these are parts of continents covered by seas, such as the North Sea and the Baltic Sea, the northwestern Black Sea (Odessa Bay), the Sea of Azov, the northern Caspian Sea, and the Barents Sea and Kara Sea in Europe; and the shallow part of the Sea of Okhotsk, part of the Bering Sea, the South China Sea, and the Yellow Sea on the margins of Asia.

The ocean-type-crust underlies the floor of all the oceans: Pacific, Indian, Atlantic, and Arctic. According to the latest data, this type of crust also underlies many deep inland seas with a flat floor surrounded by a clear-cut bench of the continental slope. True, the crust is much thicker here than under the oceans because of the considerable thickness of sedimentary rocks resting directly on the basaltic layer of the earth's crust. This thickened oceanic crust has been detected under the Mediterranean Sea, the Gulf of Mexico, the Black Sea, the southern Caspian Sea, and the seas separating the islands of Indonesia (Banda, Flores, Sulu, Celebes, and Ceram).

Studies of the crust under the Black Sea (V.P. Neprochnov, 1965) have shown that its granitic-metamorphic layer gradually thins out to the south of the Crimean coast and is missing under the Black Sea floor. Although this crust is much thicker (28 km) than the ordinary oceanic one, they are similar, that is, here a basaltic layer is present and is overlain by a thick sedimentary cover (as indicated by geophysical evidence). The same can be observed under the southern Caspian Sea (I.P. Kos'minskaya, 1959), where the 40-km oceanic-type crust is covered by thick sediments, and also under the deeps of the Mediterranean.

Therefore, all deep depressions of the earth's surface are underlain by an oceanic-type crust, and the bulges of continental masses, by a continental-type crust, which contains a more or less thick granitic-metamorphic layer.

Although the crust under oceans and inland seas is similar, considerable structural and historical differences are found. In recent years this fact has attracted much attention in connection with the nature of the M-discontinuity.

The problem is a most perplexing one. The M-discontinuity is undoubtedly a sharp physical interface between the earth's crust and the mantle and marks an abrupt increase in density. As mentioned above, the upper mantle is most probably composed of ultrabasic rocks—peridotites—taken to the surface mainly along deep-seated faults cutting through the earth's crust, such as in the Urals, Sayan, and Minor Caucasus (Lake Sevan).

Thus there is evidence supporting the view that the upper mantle consists of peridotites. On the other hand, the available data indicate that at sufficient temperatures and pressures, and because of metamorphism and compaction, rocks of the basaltic layer can be replaced by granulite and eclogite, whose physical properties are similar to those of garnet and spinel peridotites. The chemical composition of these rocks is identical with that of gabbro, basalt, and other basic rocks. Although pyroxene-garnet rocks are indistinguishable from peridotite in elastic properties and density, they have been derived from the basaltic layer and their mineralogic composition is quite different. It would thus be natural to suppose that the M-discontinuity is in some places a boundary between the mantle and the earth's crust and, in others, an interface between rocks of different density within the basaltic

layer of the crust. The possibility cannot be ruled out that beneath the inland seas (Mediterranean, Black, and others) the interface postulated as the M-discontinuity actually lies inside the crust while the true crust-mantle interface is deeper and has not yet been detected by geophysical techniques. These possibilities should be taken into account if we are to get a proper insight into the structure of the crust under the continents and ocean basins.

It can be seen that the principal elements of the face of the earth—continental masses and ocean basins—differ not only in their topography, but also in the structure of the earth's crust. No doubt, these differences are due to the entirely different histories and modes of formation of the two types of the earth's crust.

The geophysical evidence obtained in the past few decades has so far yielded only an extremely general picture of the oceanic crust. Also, little is known about the ocean floor geology.

On the other hand, we have satisfactory knowledge of the continental crust, owing to extensive geological studies in all the parts of the world. We can now draw some conclusions as to the widely different structure of the various parts of the continents, the principal stages of their formation, and their ages.

AGE OF THE EARTH'S CRUST

Geology is a historical science that studies successive events taking place over a certain time interval and takes into account their age and duration. While human history spans intervals of thousands and tens of thousands of years, geology treats tens and hundreds of millions of years. The oldest rocks of the continental crust were formed about 3 800-3 600 million years ago, and the rocks of the basaltic layer and the mantle, as many as 4 000 million years ago. From astronomical and radiological estimates, the earth's age is 5 000-4 500 million years.

The geologic time scale is based, above all, on the evidence provided by fossil animals and plants, whose evolution makes it possible to establish the relative ages of the strata containing them. In other words, by studying fossil organisms, we can determine whether one layer is younger or older than another, without specifying their absolute ages.

As a result of studies of assemblages of fossil animals and plants, several major successive time spans, called eras, have been distinguished: Archean, Proterozoic, Riphean, Paleozoic, Mesozoic, and Cenozoic. Each of the first two is many times longer than the other three combined. Hence the Archean has recently been subdivided into the early Archean and the Archean proper. The late Proterozoic has been isolated and classified as the Riphean. The Paleozoic, Mesozoic, and Cenozoic are often jointly called the Phanerozoic, or "historical eras" of the earth's evolution. It was only during those eras that organic life really flourished on earth.

Since Paleozoic (Cambrian) times, sediments of old sea basins have accumulated enormous amounts of faunal remains, such as fossil skeletons of invertebrata, which suggest a wide and vigorous development of life.

Table 2

Geologic Time-Stratigraphic Scale

Era (erathem)	Period (system)	Epoch (series)	Age (stage)
Cenozoic	Quaternary (Anthropogene)		
	Neogene	Pliocene	Late (Upper) Middle Early (Lower)
		Miocene	Late (upper) Middle Early (Lower)
	Paleogene	Oligocene	
		Eocene	Alminian Bodrakian Simferopolian Bakhchisarayan
		Paleocene	Kachinian Inkermanian
Mesozoic	Cretaceous	Late (Upper)	Danian Maestrichtian Campanian Santonian Coniacian Turonian Cenomanian
		Early (Lower)	Albian Aptian Barremian Hauterivian Valanginian Berriasian
	Jurassic	Late (Upper)	Tithonian (Volgian) Kimmeridgian Oxfordian Callovian

Table 2 (cont.)

Era (erathem)	Period (system)	Epoch (series)	Age (stage)
Mesozoic	Jurassic	Middle	Bathonian Bajocian Aalenian
		Early (Lower)	Toarcian Pliensbachian Sinemurian Hettangean
	Triassic	Late (Upper)	Norian Carnian
		Middle	Anisian Ladinian
		Early (Lower)	Olenekian Indian
Paleozoic	Permian	Late (Upper)	Tatarian Kazanian Ufimian
		Early (Lower)	Kungurian Artinian Sakmarian Asselian
	Carboniferous	Late (Upper)	Gzhelian Kasimovian
		Middle	Moscovian Bashkirian
		Early (Lower)	Namurian Viséan Tournaisian
	Devonian	Late (Upper)	Famennian Frasnian
		Middle	Givetian Eifelian

Table 2 (cont.)

Era (erathem)	Period (system)	Epoch (series)	Age (stage)
Paleozoic	Devonian	Early (Lower)	Emsian Gedinnian Coblenzian
	Silurian	Late (Upper)	Late (Upper) Ludlovian Early (Lower) Ludlovian
		Early (Lower)	Wenlockian Llandoverian
	Ordovician	Late (Upper)	Ashgillian Caradocian
		Middle	Llandeilian Llanvirnian
		Early (Lower)	Arenigian Tremadocian
	Cambrian	Late (Upper)	
		Middle	Mayan Amgian
		Early (Lower)	Lenian Aldanian Tommotian
Late (Upper) Proterozoic (Riphean)	Vendian Late (Upper) Riphean Middle Riphean Early (Lower) Riphean		
Middle Proterozoic			
Early (Lower) Proterozoic			
Archean			

The evolution of animals, whose fossil remains are found in the Paleozoic, Mesozoic, and Cenozoic strata, has enabled scientists to draw a fairly clear picture of the history of the organic realm of that period and to reconstruct events in the earth's life: changes in the configuration of the continents and oceans, in the climate, and in the structures of the earth's crust within platforms and geosynclines.

The Paleozoic, Mesozoic, and Cenozoic eras are subdivided into geologic periods (Table 2). It is appropriate to recall that geology uses two parallel scales, one for time intervals and the other for the corresponding strata and intrusive masses and other formations composing the earth's crust. Hence when we distinguish eras as time divisions of the earth's history, the respective divisions of the earth's crust are erathems. Further, systems within the erathems correspond to periods of time. Systems are divided into series and stages, and periods into epochs and ages.

Such subdivisions are adopted only for the Cenozoic, Mesozoic, and Paleozoic eras and their constituent periods. As we pass on to the older strata of the earth's crust, this classification ceases to apply, because the organic remains, on which stratigraphy is based, are absent.

In the Riphean, fossils are scarce, being represented mainly by traces of life activity of stromatolites, peculiar ancient blue-green algae. In some places products of their growth make up entire dolomite and limestone beds. They are under study mainly by Soviet geologists and paleontologists, who have proved their stratigraphic importance. It has been found that certain types of their products are confined to definite strata which are thus identifiable in various widely spaced localities and may be referred to as contemporaneous. This is clearly important for further investigations into the upper Proterozoic sediments, all the more so as the Riphean spanned a time interval exceeding the Paleozoic, Mesozoic, and Cenozoic combined. At present, we can only subdivide the Riphean into series of strata and formations of purely local extent. The situation is even worse with the classification of the lower Proterozoic and Archean. They are practically devoid of organic remains; only organic rocks are known, which suggest the existence of primitive life in those times.

Proterozoic and especially Archean sedimentary rocks are invariably altered by metamorphic processes. Hence, their correlation over great distances is extremely unlikely if not altogether impossible. Even the boundaries of the Riphean, Proterozoic, and Archean are still debatable.

It was not until the 1940s that physicists helped geologists by radiometric dating of minerals and the rocks containing them. By this technique we can establish the absolute age, that is the time of formation, of a mineral or rock, usually reckoned in millions of years. We can also correlate strata and rock complexes by their ages and establish their sequence. In recent years much attention has been given to the radioactive decay of atomic nuclei, especially uranium. Decay is a sort of imperfect clock; it shows the approximate age of minerals and rocks within a few million years, or up to 50 or even 100 million years for older Precambrian formations. But during the past 10-15 years the techniques have been considerably perfected and are now very promising.

The age of minerals, and hence the rocks containing them, is now found

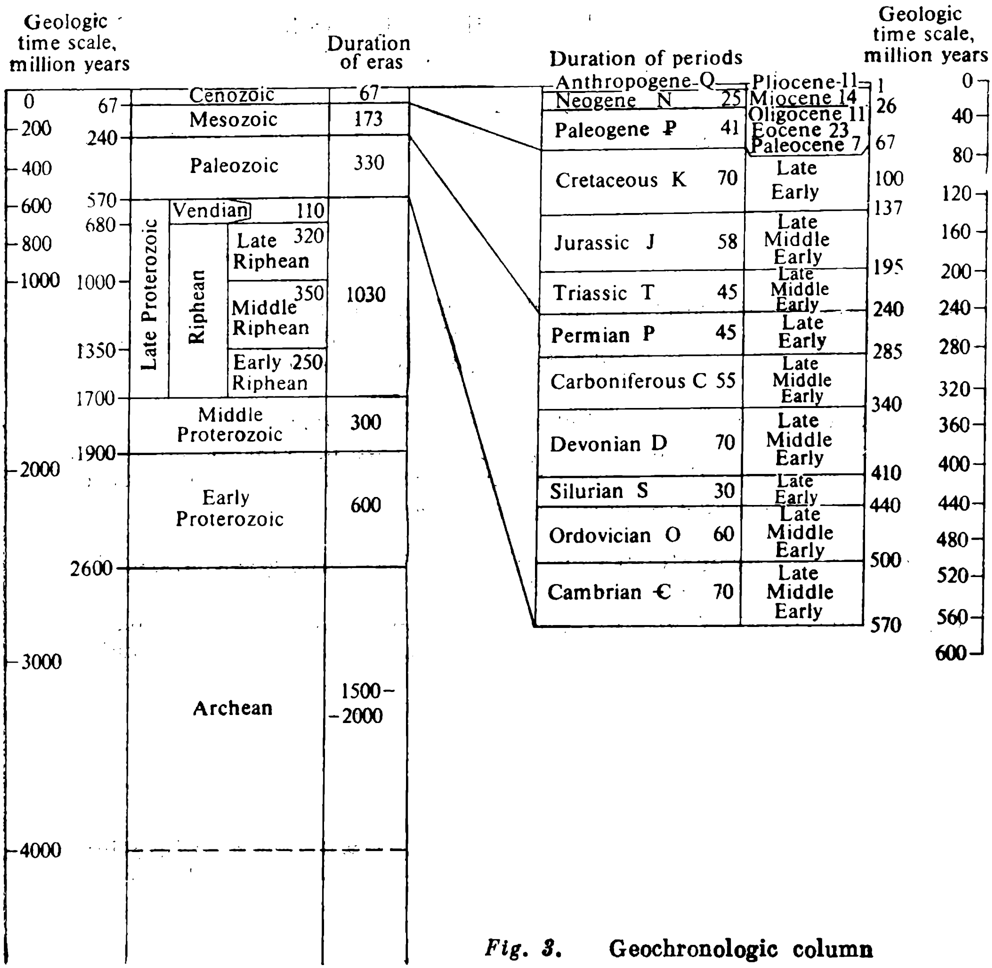


Fig. 3. **Geochronologic column**

from the age of the constituent radioactive elements and their decay products. A quantitative ratio is determined between the atoms of the radioactive element and those of its end product. Given the rate of decay, the date of formation of a given mineral can be established.

The most reliable results can be provided by determining the content of uranium and its final decay products, lead and helium, in minerals

$$^{238}U \rightarrow {}^{206}Pb + 8He$$

Uranium is known to decay into thorium, then radium, and, finally, lead. By counting lead atoms, we can find out how many uranium atoms have decayed and within what time.

In recent years the potassium-argon method, developed by Soviet scientists E.K. Gerling, G.M. Ermolin, and others, has gained wide recognition. It is based on the transformation of the radioactive potassium isotope into

argon: $^{40}K \rightarrow ^{40}Ar$. Because potassium-containing minerals are common in nature, they are very convenient for dating by this method. The most frequently used minerals are micas (muscovite and biotite) from igneous rocks or schists and gneisses, and glauconite which contains potassium and is widely distributed in marine sedimentary rocks.

To illustrate the role of geologic time in the evolution of crustal structures and the importance of the duration of the various stages, we present in Fig. 3 a geologic time scale based on a very large number of available dates for rocks and minerals found in a variety of systems and regions. The source materials are published periodically by the USSR Academy of Sciences' Commission on Geological Dating.

Therefore, we can now estimate not only the relative ages of parts of the continental crust, but also, albeit approximately, the absolute ages of geologic events.

The oldest rocks of the earth's crust make up the basaltic layer of the continents. The oldest gneisses, amphibolites, and other crystalline rocks found in ancient parts of the continents on the East European, North American, Siberian, African, and other platforms were generated about 3 600-3 800 million years ago. The Archean lasted 2 500-3 800 million years and the Proterozoic, including the Riphean, from 2 500 to 570 million years ago. Within the latter, the early and middle Proterozoic continued from 2 500 to 1 600 million years ago, and the Riphean from 1 600 to 570 million years ago.

The remaining eras, Paleozoic, Mesozoic, and Cenozoic, during which the continents and oceans and the animals and plants inhabiting them originated, span 570 million years. This relatively short period of the earth's history constitutes only 16.5 percent of the age of the crust and 12 percent of the history of the earth as a planet.

The data on the events in the geologic evolution of the continents, together with absolute age dates, permit us to estimate not only the approximate age of the crust, but also the duration of the principal stages of its history.

It is much more difficult to estimate the age of the oceanic crust. The time of its formation is judged by the relationship between the continents and ocean basins, and by other indirect data.

II

CONTINENTAL CRUST

INHOMOGENEITY OF THE STRUCTURE

The continental crust is extremely complex in structure and has a long history. This relates, above all, to its upper part composed of sedimentary rocks and a granitic-metamorphic basement. The structure of the lower crust—the basaltic layer—is still largely unknown.

Regions differing in topography and structure, basically mountain areas and plains, are distinguished on the continental surface. Some are underlain by intrusive and metamorphic rocks, others by volcanic rocks, and still others by sedimentary rocks either lying almost horizontally or forming complex systems of folds and diverse fold structures.

Five basic processes affect the earth's crust: (1) weathering and erosion of ancient rocks making up the earth's crust and transportation of fragmental material and its deposition as sediments, together with volcanic products, on the floor of seas, oceans, and lakes and on the surface of plains and depressions; (2) deformation of the strata, mostly folding; (3) intrusion of igneous masses and volcanism; (4) metamorphism of sedimentary and igneous rocks and (5) metasomatism and granitization.

Volcanic and sedimentary formations settle on the bottoms of depressions, mainly within the sea floor. Volcanism is always associated with deep-seated faults in the earth's crust. Along these faults, channelways are formed thus permitting volcanic products to move from the depths on to the earth's surface where they give rise to volcanoes. These outpour lava and expel volcanic ash and ejecta which are deposited on the sea floor and are then transformed to tuffs and breccias.

Accumulating on the sea floor, lava and tuff layers generally alternate with marine sediments, such as clayey mud, sand, and carbonate and siliceous muds which are then compacted into sedimentary rocks. Protracted

deposition of marine sediments and eruption products results in a very thick series. The slow subsidence creates a kind of a trap for marine sediments, which are laid down here to considerable thicknesses increased even further by the ingress of eruption products.

Movements in the earth's crust cause all these sedimentary and volcanic series to be involved in deformation, including folding.

The simplest types of folds in bedded rocks are anticlines and synclines (Fig. 4). Larger and more complex forms are called anticlinoria and synclinoria (Fig. 5). The beds deposited on the bottom of a sea basin are deformed into systems of folds thrust upon each other and piled up into intricate shapes. Their structure is often very difficult to decipher.

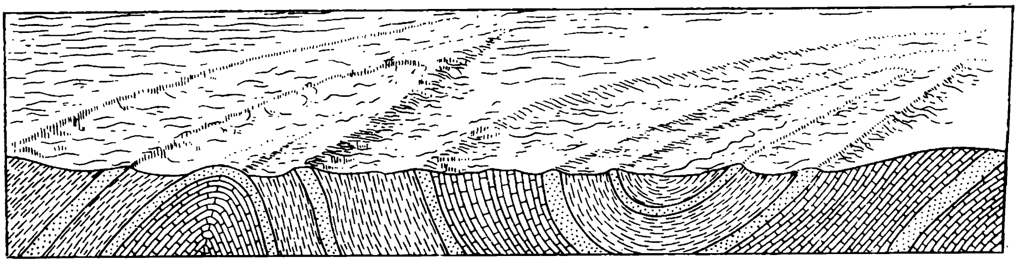


Fig. 4. A cross-section and an exposure of anticlinal and synclinal folds

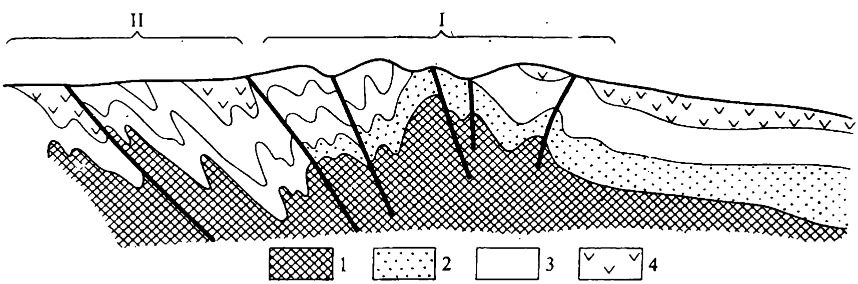


Fig. 5. A cross-section of an anticlinorium (*I*) and a synclinorium (*II*):
Sediments:
1 — Paleozoic;
2 — Triassic;
3 — Jurassic;
4 — Cretaceous

Fold structures are occasionally cut by minor faults (as compared with deep-seated faults), which can also be rather long and are either overthrusts or normal faults. Faults of different size and age often intersect, complicating the fold structures still further (Fig. 6).

The crustal movements that cause deformation differ in intensity. Strongest throughout the folding epochs, they are often accompanied by intrusions of magmatic rocks, mainly granites. Magmatic rocks invade and in many places partially melt fold structures, causing contact alteration and metamorphism of the intruded rocks.

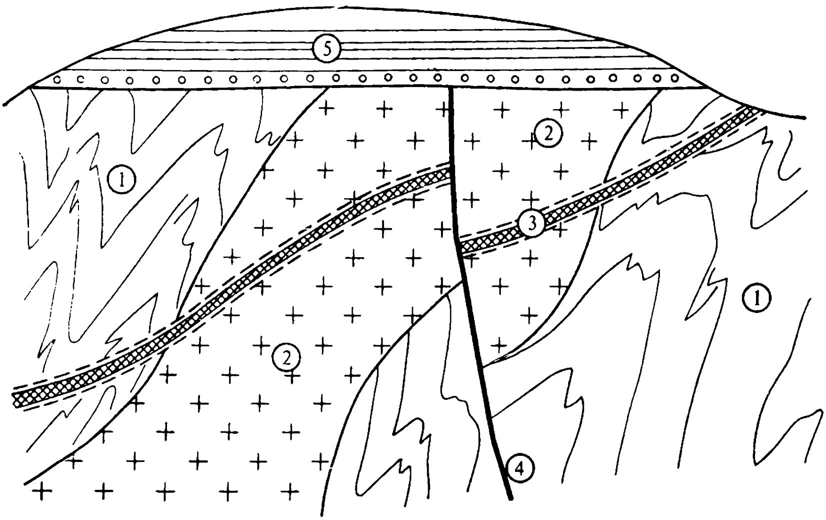


Fig. 6. A diagrammatic cross-section of the basement of a platform:
1 — sedimentary layers;
2 — granite body;
3 — ore vein;
4 — fault cutting across basement;
5 — unconformable sedimentary cover

Igneous rocks are divided by chemical composition into acid, or granitic; basic, or gabbroic; ultrabasic; and alcalic, a special group. Rocks richest in silica (SiO_2) are called acid, less rich, intermediate, even less rich, basic, and the poorest, ultrabasic. Alkalic rocks stand aside; they contain more Na_2O or Na_2O plus K_2O. Naturally, differences in chemical composition determine differences in the mineralogic composition of these subdivisions.

Extrusive rocks and tuffs are associated with, and similar in composition to, intrusive rocks, but have a different mode of occurrence and are fine crystalline.

Generalizations have been made as to the composition and origin of igneous rocks after large-scale studies of their chemical composition and the physico-chemical aspects of their crystallization, and after an extensive examination of their thin sections under the microscope. As far back as the last century, many rock types and species were singled out and their classification was developed. The progress of petrology during the past two or three decades has led to a deeper understanding of the basic physical and chemical conditions under which the various types of intrusive and extrusive rocks have formed.

Igneous rocks have, no doubt, been derived from a source (basaltic) magma which rose along faults from deep in the mantle (asthenosphere) and entered the earth's crust.

As follows from the relationships and compositions of various igneous rocks, all their diversity relates to the changes and the transformation of this source magma as it invades the earth's crust and then consolidates and crystallizes. In these processes, it is of immense importance that the magma

interacts with, and even partially melts and assimilates, the earlier consolidated rocks of different composition and sedimentary and metamorphic rocks.

The magmatic melt originates in the mantle's deep interior. The upper mantle is now considered to consist mainly of solid spinel and garnet peridotites. But a melt from it would be richer in SiO_2, that is, correspond in composition to basaltic magma. The upper mantle's plastic layer, called asthenosphere, reaches from approximately 60 kilometers beneath the oceans and 100 to 120 kilometers beneath the continents to 250-400 kilometers. Mantlelike melts and their crystallization conditions at different laboratory temperatures and pressures were studied to visualize the probable chemical composition and physical properties of the asthenosphere's material. Moreover, earthquake-produced waves traveling through the mantle were recorded by high-precision seismographs.

We may conclude that the asthenosphere is composed of pyrolite, a hypothetical material consisting of one part basalt to three parts ultrabasic material. Partial melting of pyrolite is considered to produce a magmatic melt basaltic in composition, while the residue is an ultrabasic rock. The asthenosphere's pyrolite is thought to be entirely molten at places, the melt being full of suspended solid ultrabasic rock particles.

The faults cutting through the earth's crust and upper mantle, particularly those delineating geosynclinal troughs, are conduits for the ascending plastic basaltic magma. On its way upward it may accumulate at the top of the mantle or in the lower crust to form deep-seated magma chambers. These are replenished from below by the new batches of the basaltic magma and even expand while heating the surrounding rock. Magma chambers are occasionally so large that they remain molten for a very long time. During so long a period, the material of the chamber is redistributed; this process is called magmatic differentiation. The minerals in the chamber crystallize very slowly. The most refractory minerals containing iron, magnesium, and calcium (pyroxenes and basic plagioclases) settle down first. As a result, the heavy constituents leave the upper part of the chamber, drifting down gradually. Thus the magma differentiates into a heavier (basic) portion below and a lighter portion, rich in silica, above. On the completion of crystallization of such a chamber, magma-derived gabbro can be found in its lower part and diorite or granodiorite in its upper part.

The chambers come into contact with sedimentary and metamorphic rocks, causing them to be partly melted and assimilated. Because of assimilation, the magma changes in composition: it becomes more acid, that is, richer in SiO_2, and forms, upon crystallization, the rocks of the granitic series: granite, adamellite, monzonite, granodiorite, and others. All of them may form large magma bodies intruding along faults from below into sedimentary folded sequences and cutting and fusing them. Moreover, while intruding, the magmatic melt significantly raises sedimentary strata, acting like a giant hydraulic press. Intrusive magmatic bodies are seen to be younger than their enclosing sedimentary rocks and in many places even younger than folds. This is easy to establish, because we can observe the magmatic bodies invading folded sequences and cutting and occasionally fusing the rocks involved in the folding (see Fig. 6).

In other places intrusions, mainly of basic rocks (gabbroids), invade before folding; they are detached and involved in the folding.

As a result of protracted magma transformation, intrusive masses are made up of igneous rocks varying in composition, interrelated in origin, and forming one series.

The same is true of the respective lavas (basalt, andesite, dacite, liparite, and others) outpouring onto the surface through volcanoes.

Alkalic and ultrabasic rocks stand somewhat by themselves. Alkalic rocks, which most frequently contain excessive sodium, result from the assimilation of various sedimentary rocks, particularly carbonate and clayey, by an acid granitic magma. These rocks disturb the relationship among the constituents of the magma thus enriching it in alkalis.

Ultrabasic rocks—peridotite, pyroxenite, and others—are formed quite differently and may be divided into two groups. The first is associated with basic basaltic magma and its crystallization under specific conditions: portions poorest in silicic acid differentiate from the melt to form, together with gabbro and other basic rocks, ultrabasic masses. Completely different, the second group comprises peridotites that once made up sheets and blocks in the upper mantle. Being in a plastic or solid state, these then rose along faults through the overlying crust toward the surface. Hence these rocks are invariably related to major fault-zones and are often accompanied by basic lava flows and intrusive masses. Combinations of peridotites, gabbro intrusions, and basic (diabase) lavas and tuffs are called ophiolitic complexes, or associations. These are characteristic of fault-zones in geosynclinal fold areas, and are also known from mid-oceanic ridges.

Metamorphism—sedimentary rock recrystallization at high temperature and pressure and by hot solutions introduced from below—is very important in the alteration and deformation of sedimentaries. As a result, clayey-sandy rocks are converted into various schists, gneisses, and quartzites; basic tuffs and lavas into amphibole gneisses and amphibolites; and limestones and dolomites into marbles.

Metamorphism is frequently effected by intrusive masses that transfer an immense amount of heat into the surrounding rocks and are sources of hot gaseous emanations altering these rocks. Metamorphism around intrusive masses is called contact metamorphism. In this case metamorphism involves a more or less thick zone of various enclosing rocks near their contact with the untrusive. The zone may be relatively thick, but often is only a few meters, even centimeters in thickness.

General, or regional metamorphism, which plays a greater role, is independent of intrusive bodies, but relates to the fact that while parts of the earth's crust are buried to a greater depth, their constituent sedimentary or volcanic rocks undergo higher pressure and temperature and are affected by vapors or gaseous emanations rising from depths along fissures and carrying various elements and compounds. The metamorphic processes combine to embrace extensive areas and huge volumes of the earth's crust; they are of regional extent, hence the name of this type of metamorphism.

Three major regional metamorphic facies are distinguished, depending on the thermodynamic environment. The facies differ in mineralogic composition; they contain index minerals, which develop under particular sets

of temperature and pressure conditions, and hence their modes of formation can be discerned.

The chlorite-cericite schist facies reflects the relatively low temperatures and pressures at which minerals of various schists are formed.

The amphibolite facies indicates considerable depths and high temperatures. The processes take place in rocks whose minerals, particularly amphiboles and micas, the major minerals of the facies, contain water.

The granulite facies is marked by even higher pressures and temperatures and by the lack of water. (Granulite is a hypersthene-garnet gneiss without micas and amphiboles.)

In addition, a special glaucophane schist facies originates at relatively low temperatures but high pressures. It occurs mostly in major fault-zones and geosynclinal areas, where conditions of strong stresses prevail.

Metamorphic rocks—mainly the amphibolite facies, that is, various gneisses and crystalline schists—are spread over vast areas within many ancient rock masses; they actually compose most of the basement of all the ancient platforms. The metamorphic rocks of amphibolite facies are associated with major and minor granite masses.

Metamorphic processes are under way in the deep interior of the earth's crust, and we cannot of course observe them directly. By uplifting and erosion, the deep crustal zones become exposed; thus, the results of metamorphism can be observed directly, particularly over the vast ancient shields, the oldest parts of the continents.

As has been found in the past few decades, metasomatism causes rock transformation over vast areas. Academician D.S. Korzhinsky and his school have contributed much in this field.

Metasomatism is the transformation of minerals of igneous, sedimentary or metamorphic rocks by active solutions containing various compounds. These are water fluids that occur in the deep interior of the crust and hence are in the supercritical, vaporous state, and are severely compressed. In addition, they contain carbonic acid, sodium and potassium chlorides and lesser amounts of other elements in solution.

The fluids chemically alter primary minerals and form new ones. At the same time, certain minerals may decompose, so that the resulting rock has a different composition, namely is rich in secondary minerals but poor in primary ones. The replacement process occurs at constant volume, that is, the amount of material introduced equals that expelled.

Therefore, metasomatism differs substantially from metamorphism. The point is that under the metamorphic action of high temperature and pressure the mineralogic composition of a rock is altered while its chemical composition remains basically the same. In contrast, during metasomatism, the solutions penetrating into the rocks greatly alter the chemical composition of their constituent minerals.

Metasomatic solutions originate deep within the magma and then rise through it, prompting D.S. Korzhinsky to call them "through-magma solutions". On their way along fault-zones, fractures, and other tectonically weak zones, they affect the enclosing rock. Diffusion of solutions, that is, their penetration through pores and the intermolecular space, can also bring about metasomatic alterations.

Metasomatism is most prevalent and very active at the contacts between the molten magma and the enclosing rock. Depending on the chemical composition of the latter and the activity of the fluid, the rock may be altered drastically, sometimes with the formation of various ore minerals which may concentrate. Metasomatic processes often act not only at the contact, but also very far from it.

Quite characteristic is metasomatism during which alkalis (Na and K compounds) are introduced. For example, albite, the sodium feldspar, may appear or increase in amount, so the resulting rock may be enriched in it.

Potassium metasomatism is also of great importance. It often leads to the formation of granite from the various sedimentary or metamorphic source rocks. The process, called granitization, has been extensive in the deep interior of the crust throughout the earth's history.

Generally speaking, at depths of many kilometers in the earth's crust, pressures and temperatures are high enough for anatexis to occur. However, the chemical composition of most granites cannot be accounted for only by the melting of some mean mass of sedimentary or metamorphic rocks. For example, it was calculated that the potassium content of these rocks is lower than that of average granite. Hence we have to assume the introduction of material, particularly potassium and silicon, that is, the action of potassium metasomatism.

By granitization D.S. Korzhinsky means that magma-derived fluids introduced from below and rich in volatiles metasomatically alter rocks near the contact; then, following the action of metasomatism, these rocks are replaced by a magmatic melt. A kind of a metasomatic front originates moving away from the magma and is followed by a melting front which leaves behind great amounts of melt, a secondary magma.

The melt is then crystallized to form large granite masses. At the same time, some of these granite masses were probably derived exclusively by melting alone, without metasomatism; however, they are smaller and more restricted.

In the areas of Precambrian metamorphics within the basement of ancient platforms, granitization is accompanied by migmatization which is extensive on the margins of granite masses. The resulting rock complex consists of gneiss and schist layers with granite veinlets. Migmatites formed at the same time as the granites and by the same processes. They are often wrinkled, which indicates that they were in a plastic state during the deformation.

UNCONFORMITIES AND THEIR SIGNIFICANCE

To date the folding and faulting and the general crustal movements that have caused deformation, we have to establish the sequence of events. At the outset, we should determine when the relevant sediments were laid down and then when they were deformed, intruded, metamorphosed, and so on. Only in this way can we reveal the age of a particular structural feature. Accordingly, it is especially important to trace and date unconformity surfaces in sedimentary and volcanic strata. An unconformity surface is a sur-

face at the base of a layer resting on other earlier deformed older layers and rocks.

If a sea had filled a basin from the very beginning to the present and sediments had been constantly deposited on its floor, a continuous succession could be observed from the oldest Precambrian to the youngest Neogene or the Quaternary. This would indicate that the basin has remained the same from the very outset, and particularly that no crustal uplift has taken place within its limits. The possibility cannot be ruled out that the central Pacific is the oldest of such basins. Here, marine sediments accumulated not only throughout the Mesozoic and Paleozoic, but possibly even earlier.

As to the continents, continuous sequences are nowhere present, not even in the deepest known basins; instead, they can be subdivided into differently lying suites. Surficial strata generally lie flat or are gently inclined, deeper strata lie steeper and still deeper strata are folded and metamorphosed. The members and formations dipping at different angles are invariably separated by breaks in deposition or by unconformity surfaces (Fig. 7). These indicate crustal movements, postdepositional uplifting, and the deformation of the underlying rocks.

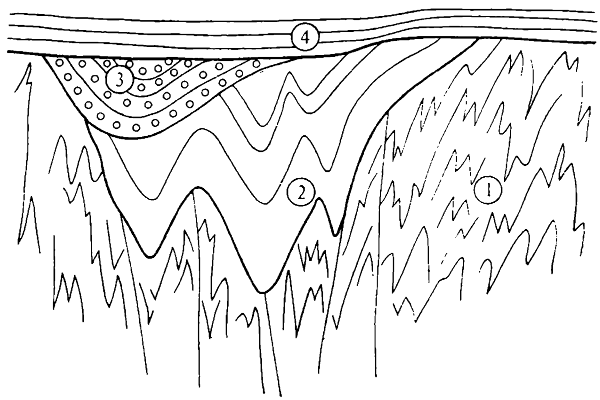


Fig. 7. A complicated fold structure composed of four variously occurring rock complexes separated by unconformities (solid lines)

Unconformity studies can provide important clues to the history of crustal movements and tectonic structures; they were first undertaken as early as the middle of the 17th century by Nicolaus Steno, a Danish scientist who worked in Italy. This technique served to develop the theory of unconformities and episodes and epochs of folding.

The essense of determining the age of folds is that a fold structure is always younger than its involved beds and older than the layers that rest unconformably on the eroded surface of this structure. In the same way we can determine the age of a fault or an ore vein.

Having determined the age of the layers involved in folding and of those that overlie the fold structure but are not folded, we can establish the time interval the folding spanned, often called folding episode. In fact, far from all the unconformities are associated with a folding episode. Most of them reflect broader movements in the earth's crust, but the above considerations

remain the same. Thus it is important to determine the role of unconformities and folding epochs.

An unconformity may be local, suggesting that at a certain moment of geologic history folding, faulting, and igneous intrusion took place in the area. If no unconformity is present in the neighboring areas, it is of local extent and was formed by local folding.

Unconformities may be spread over a large fold belt, indicating certain phases (if unconformities are numerous) in its history.

Several successive tectonic events that have led to the formation of large and extensive unconformities can be grouped into epochs of folding.

Folding epochs divide the history of the major sections of the earth's crust into stretches often called tectonic cycles. The time of their completion is very important in establishing their ages. By radiometric dating we can delimit the period of unconformity that marks the termination of a tectonic cycle. The duration of a folding epoch can also be known from the age of the rocks, especially the granitic, that were intruded at its end.

The age of metamorphic processes is also of considerable importance, because they often coincide with, or postdate, folding. It should be borne in mind, however, that the age of metamorphic minerals, for example, mica of gneiss, reflects merely the age of metamorphism, not of the source sedimentary rock.

The minerals of ore bodies associated with granitic intrusions, such as pegmatites, aplites, ore veins, and other bodies (uranium- and lead-bearing minerals are frequently present in them), often precipitate during major foldings; hence their age plays almost the same role as the age of an unconformity surface.

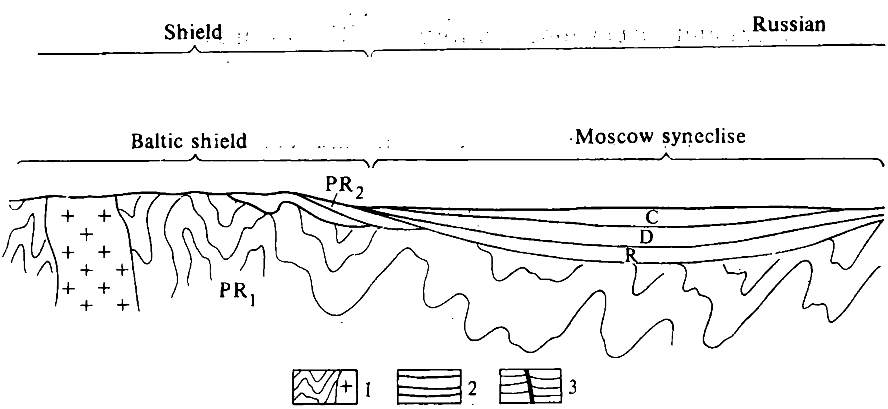


Fig. 8. A diagrammatic cross-section of major structural units of ancient platform

1 — crystalline basement of platform with intrusions;
2 — sedimentary cover of platform;

Sediments:
P_1P_2 — Permian;
C — Carboniferous;

EVOLUTION OF FOLD AREAS AND FORMATION OF PLATFORM BASEMENT

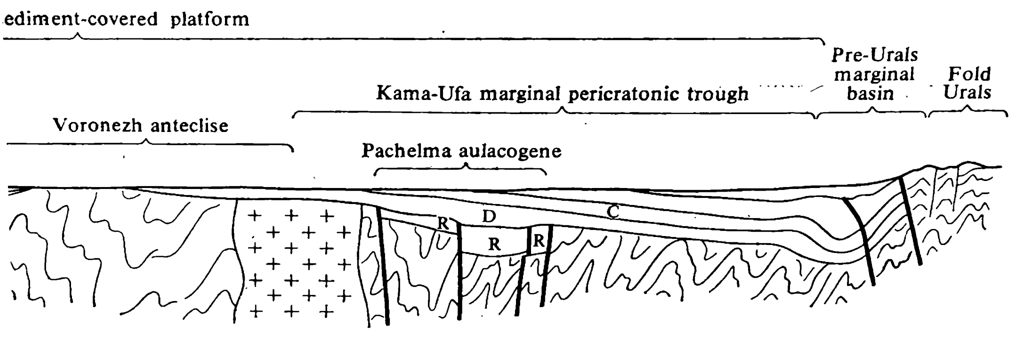
By unconformities, we can subdivide sedimentary and metamorphic sequences into complexes differing in the age of sedimentation, folding, and intrusion, and distinguish certain stages of the crust's evolution in a given area.

Sediments are deposited upon the floor of water bodies—oceans, seas, and lakes—and, to a lesser extent, on the land surface. Since depositional rates are different for different environments, the thickness of the strata is varying. To prove this, pay attention to present-day depositional conditions.

With their great depths and immense floor area, the oceans very slowly accumulate a relatively thin layer of sediments, including ooze, which is due to a poor supply of clastic debris and its areal dispersion.

The situation is different in deep sea basins surrounded by islands or continents, such as the Mediterranean Sea, Black Sea, and Caspian Sea. Rivers transport much sand and mud into the seas. According to geophysical evidence, during the last geologic epochs—the Quaternary and Pliocene—that is, for 5 to 7 million years, more than 2 000 meters of sediment accumulated on the floor of the Black Sea, and even 5 000 to 7 000 meters on the floor of the Caspian Sea. At the same time the oceanic sediments reached only a few dozen meters in thickness.

With the earth's surface becoming sharply dissected, environments appeared favorable for the denudation of mountain ranges and highlands and for the accumulation of thick sediments in depressions in-between, which served to trap erosional products. In the geologic past these depressions were long-developing deep downwarps of the earth's crust, separated by growing uplifts. The downwarps, called geosynclinal troughs or simply geosynclines, received



ast European platform is taken as a pattern):

D — Devonian;
R — Riphean,
PR_2 — middle Proterozoic;
PR_1 — lower Proterozoic;
3 — fault

3—088

great volumes of sedimentary and volcanic rocks whose thickness occasionally reached several kilometers or even one or two dozen kilometers.

During subsequent crustal movements these rocks were folded, severely in some places, and faulted, intruded, and then metamorphosed.

Early in the development of most of the fold areas, geosynclinal troughs or even their systems originated; these are delineated by faults and show volcanic manifestations. The sedimentary and volcanic suites of these troughs were then intensely folded by crustal movements and invaded by igneous rocks. Finally, major uplifts of the earth's crust took place, with the formation of mountain topography. The unique role played by geosynclinal troughs in the above processes justifies ascribing the name "geosynclinal areas" to the places where they develop. Geosynclinal troughs are generally characterized by great crustal unrest, with violent volcanism and repeated folding and igneous intrusion. The sedimentary series within the geosynclinal area are more or less severely folded and metamorphosed. The final folding and uplift of large areas of the earth's surface are of considerable importance. Great crustal uplift and the resulting growth of mountain ranges are called orogenesis, which is accompanied by the formation of intermontane basins and troughs.

These processes are the most intense toward the end of the geosynclinal cycle; hence it can be subdivided into two stages: the main, of longer duration, when systems of geosynclinal troughs develop, and the orogenic, or final, when mountains rise. When these processes stop operating, the period of crustal unrest typical of geosynclinal areas appears to end, as does igneous activity and folding. The final folding marks the end of the geosynclinal cycle.

As a result of folding and metamorphism, some relatively mobile parts of the earth's crust become less mobile and cannot be further folded. They may later undergo slight bending and block faulting. The earth's crust becomes, so to speak, more massive and rigid.

Such parts of the earth's crust, which have lost their considerable mobility and cannot be folded, are called platforms. More precisely, they form the foundation (or platform basement) layer, overlain by flat-lying or very slightly deformed sedimentary rocks composing the "sedimentary cover" of platforms (Fig. 8).

Consequently, a platform consists of a basement, resulting from the deformation of a previously more mobile and easily deformable part of the earth's crust, and an essentially non-deformed sedimentary cover, which rests on the flat eroded surface of the basement. The age of the surface indicates when the mobile fold area was transformed to a platform after the folding and metamorphism of its contained rocks.

Naturally, platforms may differ in the time of their origin, that is, of the formation of their respective basements.

The continental crust is now composed mainly of platforms of various ages. Along with them, limited areas exist within which the earth's crust has not yet become a platform and hence they are present-day geosynclinal areas. These are restricted mainly to the Pacific margins of the continents of Asia and America, to the Indonesian Archipelago, and to the Mediterranean Sea and the adjoining parts of Europe, Asia, and Africa.

III

THE BASIC COMPONENT PARTS OF THE CONTINENTS: ANCIENT PLATFORMS AND FOLD BELTS

Platforms of different ages are basically classified into ancient and young, depending on how long ago their basements formed.

Ancient platforms originated in the Archean and early and middle Proterozoic; younger platforms date back to the late Proterozoic, Paleozoic, and even to the Mesozoic.

Ancient platforms are the oldest and most stable sections of the continents. Their thick basement consists of the oldest Precambrian schists and other metamorphic rocks intruded by granitic and other igneous rocks. It is actually the thickest granitic-metamorphic layer of the earth's crust overlain by sedimentary and more seldom by volcanic rocks, which make up the sedimentary cover.

In the literature, ancient platforms are often called cratons (from the Greek "kratos"—hard). The term craton was coined by G. Stille, the famous German tectonist.

Young platforms are more mobile; their granitic-metamorphic layer is, as a rule, thinner. Young platforms are often broken into systems of upfaulted and downfaulted blocks differing in tectonic activity. Many mountainous areas of the present-day earth's surface are geologically young platforms. These are parts of the Altai, Tien Shan, and Sayan in the USSR; the Ardennes, Sudetes, and Scandinavian Mountains in Western Europe; the Appalachians in America; and many others.

Ancient platforms are structurally different from younger ones. The earth's crust is thickest and most homogeneous beneath ancient platforms, reaching 30-40 kilometers and even 50 kilometers in some places. Within young platforms, the crust has a thicker basaltic layer, but in general it is fairly homogeneous, though somewhat bulges beneath mountain ranges.

The crust of the present-day geosynclinal areas is more complex. Here, it varies greatly in thickness and structure, being thicker under mountains and thinner under lowlands and basins.

According to geophysical evidence, beneath the basins of some marginal and inland seas, such as the Sea of Japan and the Black Sea, the earth's crust is similar to the ocean-type crust, differing only in the thicker sedimentary sequence.

THE IMPORTANCE OF ANCIENT AND YOUNG PLATFORMS IN THE STRUCTURE OF CONTINENTS

Ancient platforms greatly differ from younger ones in the time of their formation. It would be incorrect to say that the difference is that the former originated before the mid-Proterozoic and the latter in the late Proterozoic or later. It is much more profound and lies in the circumstances in which they formed and in their role in the structure of the continents.

The basement of ancient platforms is the oldest part of the granitic-metamorphic layer of the earth's crust. Made up of thick gneiss series and huge granite masses, it began to form as early as in Archean time (3 800-3 500 million years ago) and was evidently terminated in early or middle Proterozoic time (2 000-1 800 million years ago).

Only in the last stage did the processes similar to those in the younger geosynclinal areas start to operate.

As distinct from ancient platforms, the basement of young platforms is the result of events in geosynclinal fold areas, and their tectonic cycle is much shorter.

Ancient and young platforms play fundamentally different roles in the structure of the continents. The ancient platforms build up angular sections within the continents as if they were their nuclei. The young platforms occur between, and border, the ancient ones. With their much younger basements, they form extensive elongated strips called fold belts. These consist of fold areas which consolidated at different times. Moreover, some of the belts include present geosynclinal areas, which have not yet been transformed into platforms.

A BRIEF OUTLINE OF THE STRUCTURE OF CONTINENTS

All the continents include more or less extensive ancient platforms and intervening fold belts (Fig. 9), their basic structural units.

Eurasia includes five large ancient platforms—the East-European, Siberian, Hindustan, South China, and China-Korea, and four small—the Tarim, Kolyma, Tibet and Indosinic (in Asia), as well as the old Eire Massif in

Northern Scotland. Geologists exploring the Arctic believe that another ancient platform, the Hyperborean, underlies the ocean floor north of Eastern Siberia.

Eurasia contains four fold belts. In the northwest, the margin of the Atlantic belt runs through Ireland, Scotland, the Scandinavian Mountains, and Spitzbergen. To the east, the Ural-Mongolia belt crosses the entire Asian continent as a huge arc. It separates the European from the Siberian platform and the latter from the Tarim and China-Korea platforms.

The Mediterranean belt borders the southern side of the East European platform and separates it from the North African, Arabian, and Hindustan platforms. It includes the Mediterranean coast in Southern Europe, then passes through Iran, the Hymalayas, the Malacca Peninsula, and Indo-China, and enters the Indonesian Archipelago.

In the east, the South China, China-Korea, Siberian, and Kolyma platforms are flanked by the Circum-Pacific belt which separates the deep-sea part of the Pacific from the surrounding continental masses.

Africa includes three ancient platforms. The largest, the North African platform occupies the extensive northern and the central part of the continent; the South African platform, southern and southeastern Africa and Madagascar; and the Arabian platform, the central, eastern, and southeastern Arabian Peninsula (geographically, it is usually included in Asia, but geologically it is closely related to other African platforms).

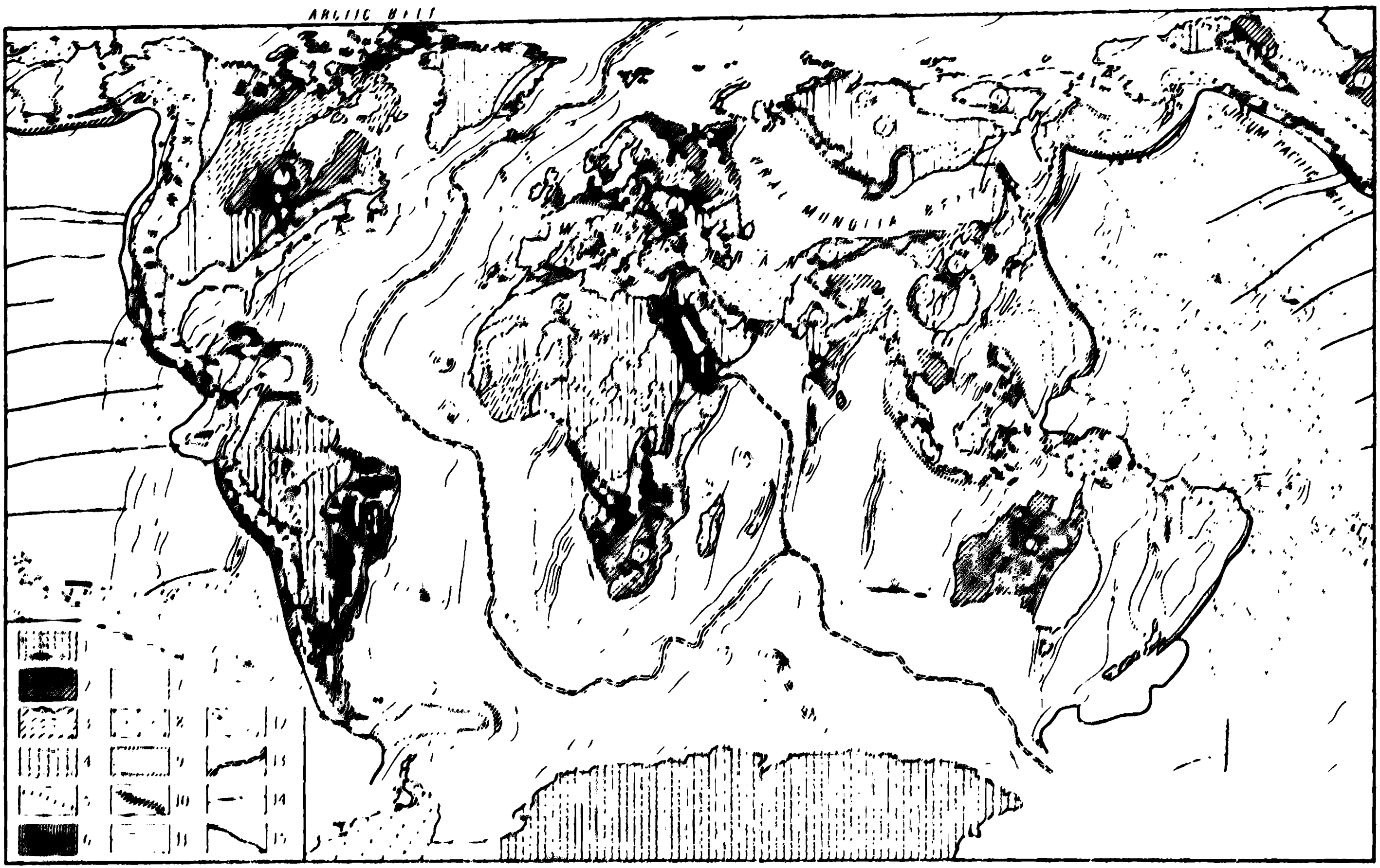
These platforms are separated by the long and relatively narrow Intra-African fold belt composed of the fold areas that consolidated at the end of the Proterozoic. One of its stretches runs along the Red Sea coast, while the other extends from Lake Victoria southward and southwestward to the Atlantic coast. It divides the North African platform and the South African platform. An outgrowth from its western part, called the West Congolese fold area, goes northwestward through Angola (along the Mayumba Mountains), crosses the lower Congo River, and terminates on the Gabon coast.

Australia consists of two major parts. The larger western part encompasses the area now occupied by the ancient Australian platform which continues northward across the near-shore shelf to, and including, the southern plains of New Guinea. Eastern Australia is tectonically a young platform belonging to the Circum-Pacific belt. This platform also includes northern New Guinea, the islands northeast and east of Australia, and New Zealand.

The foundation of North America and Greenland is the giant ancient North American platform which is vaster than all the other ancient platforms. It occupies the greater part of the continent, Baffin Island, and Greenland. Southeast of the platform, the Atlantic fold belt of America runs along the Atlantic coast of the USA, Canada, and Greenland; it is perhaps a continuation of the European Atlantic belt. Consequently, the Atlantic fold belt was broken in two by the Atlantic Ocean.

The North American platform is bordered on the northeast, along the coasts of Greenland and the North American Arctic Archipelago by the Arctic belt whose edge and western extension are cut off by the edge of the ocean basin. Hence the relationship between this belt and the others has not yet been completely elucidated.

On the west, the North American platform is bordered by the stretch of the


ARCTIC BELT
URAL MONGOLIA BELT
CIRCUM PACIFIC BELT

Circum-Pacific fold belt that extends from Asia through the Aleutian arc into Central America where it embraces the Greater and Lesser Antilles and the Caribbean Sea. Geographically, the Caribbean Sea is a bay of the Atlantic Ocean, but geologically, the fringing garland of islands and the Andes of Venezuela, like those of all of South America, belong to the Circum-Pacific belt.

Two ancient platforms are within South America: the larger South American and the smaller East Brazilian on the east coast. These are separated by the Brazilian fold belt which crosses Brazil in a north-south direction and in the south apparently runs through Argentina and Patagonia. Like the Intra-African belt, it consolidated at the end of the Proterozoic.

South America is margined on the west by the Andes mountain system. On the south, the mountains extend eastward as the Andes of Tierra del Fuego and then as a submarine ridge. Together with a group of islands (South Georgia Island, South Sandwich Islands, and others) the ridge makes up a Caribbean-like arc. It connects the Andes with the extension of the Circum-Pacific belt in the Antarctica. Here, the belt includes the fold range of the Antarctic Andes which follow the Pacific coast and the edge of the Southern continent. Outside this range, the Antarctica is predominantly the ancient Antarctic platform covered by thick continental ice.

All in all, 18 ancient platforms are recognized within the continents. The Mediterranean belt separates them into two groups, or series: the northern and the southern.

In the northern series, the ancient platforms are separated by very wide

◀ *Fig. 9.* Major structural units of the continents:

Ancient platforms:
1 — basement, undifferentiated;
2 — Archean massifs in basement;
3 — early or middle Proterozoic fold structure in basement;
4 — part of basement involved in late Proterozoic granitization (1 500-500 million years old);
5 — boundary of shield or sediment-covered areas of platform;
6 — late Proterozoic fold area of minor fold belts, folded and granitized during Dalsland, Crenville (1 200-900 million years old), Baikalian, Katangian, Brazilian, Kadomian, and Vindian (700-500 million years old) foldings or major late Proterozoic area of large belt included in young platform.

Geosynclinal fold belts:
7 — area of large geosynclinal fold belt transformed into young platform (epi-Baikalian, epi-Caledonian, epi-Hercynian, or epi-Mesozoic);
8 — part of large still mobile geosynclinal fold synclinal area;
9 — basin of inland or marginal sea within geosynclinal area;
10 — deep-sea trench.

Features of ocean floor:
11 — boundary of ocean deep;
12 — ocean rise;
13 — mid-oceanic ridge;
14 — major fault;
15 — andesitic line, boundary of Pacific thalassocraton.

Encircled figures stand for following platforms:
1 — East European;
2 — Siberian;
3 — Tarim;
4 — China-Korea;
5 — South China;
6 — Kolyma;
7 — North American;
8 — North African;
9 — South African;
10 — Arabian;
11 — Hindustan;
12 — Australian;
13 — South American;
14 — East Brazilian;
15 — Antarctic

belts composed of the fold areas of widely different ages, including late Proterozoic, while in the southern series, the platforms are separated by narrower belts consisting only of Proterozoic fold belts. The Intra-African and Brazilian belts are smaller and hence may be called minor. They had completed their development and become platforms by the end of the Proterozoic. Five other belts, which differ greatly in their histories, are called major, because they are extensive and cross many of the continents. The parts of the Atlantic belt separated by the ocean (Ural-Mongolia and Arctic) are areas whose basement had consolidated throughout the late Proterozoic and Paleozoic. Severe geosynclinal folding had been completed within these areas by the end of the Paleozoic, and since then they have been young platforms.

In contrast, the basement of the young platforms within the Mediterranean and Circum-Pacific belts have formed only in part of their territory, while vast tracts are still active geosynclinal areas. It should be noted that the Circum-Pacific belt differs in that it intervenes between the Pacific floor and the ancient platforms of Asia, America, Antarctica and Australia. It is a wide ring that embraces the border zone between the continent and ocean floor.

CONSTITUENT ELEMENTS OF ANCIENT PLATFORMS

The ancient platforms are largely blanketed by a thick sedimentary cover; hence their basement has been studied only where it is exposed or, as on the East European platform, is penetrated by a lot of boreholes.

Yet from the data on the best studied parts of the platforms we may derive a general picture of their crystalline basement and sedimentary cover.

A number of metamorphic and igneous rock complexes of different compositions and ages are distinguished in the basement of ancient platforms. These complexes are often separated by unconformities and major faults, and correspond to definite stages in the basement history. They are made up of both the oldest igneous and metamorphic rocks, whose radiometric age is more than 3 000 million years, and younger ones. It has been found that the youngest rocks of the basement of ancient platforms are early and middle Proterozoic in age, that is, 1 800 to 1 600 million years old (see Table 2).

The basement of ancient platforms contains many very large massifs of acid (granitic) rocks and smaller massifs of basic rocks. All these are mostly folded and can be assigned an Archean or early or middle Proterozoic age. The basic intrusives are made up of gabbro, norite, and highly characteristic anorthosite composed almost entirely of basic plagioclase (labradorite-anortite). They make up large massifs, mostly on the margins of many platforms. Granite rapakivis are younger, commonly middle Proterozoic, and have much in common.

It should be noted that in many places the basement of ancient platforms is invaded by late Proterozoic (Riphean) igneous complexes, much younger than the basement. Paleozoic (alkalic intrusions of the Kola Peninsula) and even

Mesozoic rocks (granitic rocks of the China-Korea and the southern Siberian platforms) have also been found.

Ancient platforms are usually subdivided into parts called shields*, where the basement is exposed, and sediment-covered platforms.

The sedimentary cover of ancient platforms consists mainly of Cenozoic, Mesozoic, Paleozoic, and Riphean (upper Proterozoic) rocks. They occasionally compose thick suites and are widespread over these platforms. The sedimentary cover is particularly thick in some deeply downbuckled basins and in certain grabens** in the basement.

The sedimentary cover fills depressions of the basement and blankets the sides of elevations. The depressions may be classified as basins, vast and gentle-sided and filled with sedimentary layers, and grabenlike elongate troughs bounded by faults on their sides. Large and complex grabenlike troughs, occasionally with fold systems, are called aulacogens.

Gently sided basins are divided into vast syneclises, rounded or oval in plan, and marginal, or pericratonic troughs, which flank platforms and are asymmetrical, with one side dipping gently. The gently sloping intervening uplifts are called anteclises or, if small, arches.

Some shields have partly retained a kind of very ancient protosedimentary cover of middle and even early Proterozoic age (South Africa, Canada, Udokan in the southern Siberian platform, and south India). Although it occurs rarely, it is extremely interesting as a witness of the oldest platform known on earth.

FOLD BELTS

As mentioned above, the fold belts consist predominantly of young platforms of various ages, and only the Circum-Pacific and Mediterranean belts include present-day geosynclinal areas.

The basement of young platforms is composed of Upper Proterozoic (between 1 500 and 600 million years ago), Paleozoic, and in some places Mesozoic rocks. It comprises fold areas of different ages and is overlain by a sedimentary cover. By the time folding is completed, late Proterozoic, Paleozoic, Mesozoic, and Cenozoic areas are distinguished.

The late Proterozoic areas can be assigned to two time intervals. In the older the folding was terminated between 1 200 and 1 000-800 million years ago and in the younger areas, called Baikalides, between 700 and 500 million years ago. According to N. S. Shatsky (1932), the area on the margin of the Siberian platform is an example. The older areas have not yet received a widely accepted name. They are most frequently named Kibarian for the Kibarian fold area of Africa, or Grenville (North America). Yu.A. Zaitsev suggests that these areas should be named Issidonian for the Issidonian folding of Kazakhstan.

The Paleozoic fold areas are also divided into two and occasionally more

* Shield is a gentle arch similar in shape to the convex oval ancient Greek warrior's shield.

** Graben is a narrow long trough bounded by faults on its long sides. Its floor is downfaulted.

groups of different ages. These are the Caledonian, whose geosynclinal cycle ended in the middle of the Paleozoic between 400 and 360 million years ago, and the Hercynian, or Variscan, which consolidated at the end of the Paleozoic between 320 and 240 million years ago.

The geosynclinal cycle of the Mesozoic fold areas had ended by Late Jurassic or early Cretaceous time, during the Nevadan folding, or by Late Cretaceous or Paleogene time (between 100 and 70 million years ago), during the Laramide folding.

According to the time of formation of the basement, the young platforms are classified as epi-Baikalian*, epi-Paleozoic, and epi-Mesozoic (epi-Paleozoic platforms are divided into epi-Hercynian and epi-Caledonian).

Like the ancient, young platforms contain elevated areas (predominantly highlands and mountain ranges) that are akin to the shields and vast and flat sediment-covered areas. These areas include grabenlike troughs called taphrogenes, syneclises, and anteclises, and some of them are extensive (Mid-European, Turan, West Siberian, and others).

Along with the regions where the geosynclinal stage and folding have come to a close, the Mediterranean and Circum-Pacific belts include today's geosynclinal areas. These are distinguished by an extremely rugged surface—lofty mountain ranges are interspersed with deep troughs and the basins of marginal and inland seas such as the Mediterranean Sea, the Black Sea and the Sea of Japan. Here, neotectonic processes operate—slow uplift and subsidence, violent earthquakes, and recent volcanism.

The contacts of the fold areas of the belts with the neighboring fold areas and platforms are faulted, the bounding deep-seated faults cutting through the entire crust into the mantle. Being the fundamental structural elements of the earth's crust, these faults are most likely responsible for the angular outlines of the ancient platforms and for many structural features of the continents. Large crustal blocks are displaced on their planes, and in some places the result is the occurrence of shatter zones and magmatic manifestations. Within fold areas, deep-seated faults delineate major structures, such as geosynclinal troughs, many of the uplifts, and separate crustal blocks. They often show intricately ramified pattern (Fig. 10).

In some areas, and occasionally in between, deep-seated faults delineate the young platforms that are somewhat older than usual. Thus the Paleozoic fold areas include the late Proterozoic (Baikalian) structures, which are at places overlain, as on platforms, by a sedimentary cover, and parts of the Mesozoic and Cenozoic areas whose final stage of evolution was marked by the Baikalian and Paleozoic folding epochs. Such older parts are called median masses. They often occupy vast expanses, as if they were platform fragments, but differ from young platforms in that the adjoining or surrounding geosynclinal systems actively affect them. As a result, some median masses are strongly disturbed by block folds and faults and intruded by igneous rocks of the type that also partially melts the neighboring fold systems. Hence we

* Epi is a prefix meaning "higher", i.e. that the sedimentary cover overlies the indicated basement.

have to regard median masses as specific constituents of fold areas, except when they occur clearly outside of the areas and separate them. The above description thus demonstrates that fold areas and belts are very complex in structure.

Minor belts—the Intra-African and Brazilian—are not only smaller than major ones, but also, as mentioned earlier, differ greatly in structure and history. In these belts, which are relatively narrow and elongated in north-south and north-east-southwest directions, geosynclinal processes started in the Archean, continued through the Proterozoic and ended in the Katanga (Brazilian, Baikalian) folding epoch, that is, 500-600 million years ago. Since then the minor fold belts have become the basement of new platforms. This basement linked together the edges of the ancient North African, South African, and Arabian platforms in Africa and those of the South American and East Brazilian platforms in America. As a result, since the end of the Proterozoic huge continental platforms of almost all of Africa and South America have emerged and have been overlain by a Paleozoic-to-Mesozoic and Cenozoic sedimentary cover. From the beginning of this century these platforms have been regarded as parts (now fragments) of Gondwana, a single giant protocontinent*. They have some common structural and historical features, including the occurrence of late Proterozoic fold areas. The platforms of the southern continents are often called Gondwanian.

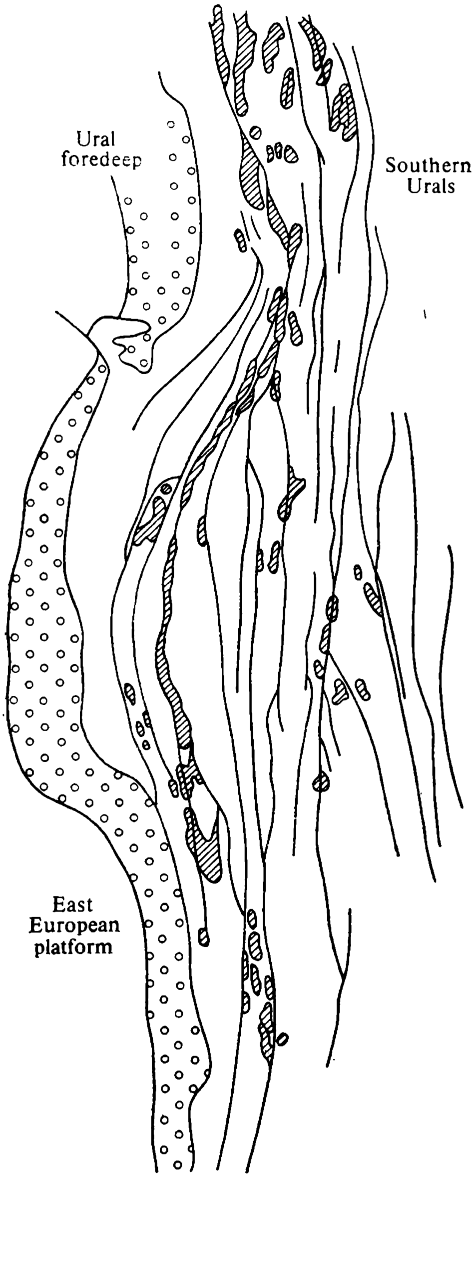


Fig. 10. The system of major deep-seated faults cutting across the fold area of the Southern Urals.

(Associated ultrabasic intrusions are shaded)

* The protocontinent was named by E. Suess for a tribe in Central India.

The major and minor belts originated, completed folding, and became basements of platforms at different times. The latter date back as mobile geosynclinal areas between ancient Archean masses perhaps to the very beginning of the Proterozoic and include parts of lower and middle Proterozoic fold systems involving metamorphic and igneous rocks of the same age. In contrast, the major belts formed late in the middle Proterozoic to early in the late Proterozoic (Riphean). In other words, the geosynclinal fold areas within the major belts started to develop 800-900 million years later than within the minor belts. Also, the major belts evolved for longer periods, and some of them are still evolving, as present geosynclinal areas indicate.

The minor belts appear to have formed by the breaking up and pushing apart of the ancient basement. During the Proterozoic, they passed through several major folding epochs in which some of their parts were folded and metamorphosed. The minor belts consolidated and became the basement of platforms late in the Proterozoic.

The history of the major belts is much longer and more complicated. Thus the Atlantic belt includes the Paleozoic fold belts located on the Atlantic coast. An example is the entire area of the Appalachian Mountains, which in the south represent the Hercynian fold system and north of New York the Caledonian system extending into the fold systems of eastern Canada, Nova Scotia, and Newfoundland. The Southern Appalachians, buried under sedimentary cover in Louisiana, Alabama, and Texas, approach the Gulf Coast in eastern Mexico. In the north, the belt extension is the fold area of the coast of eastern Greenland. On the opposite side of the Atlantic, the Caledonian fold area of Great Britain and Ireland should be included in this belt. This area and the Caledonian area of Canada and Newfoundland have many common historical features and even common faunas from certain Cambrian and Ordovician horizons. The Caledonian area of Scandinavia and Spitzbergen is the northeastern continuation. The similarity between the Paleozoic fold areas on both sides of the Atlantic Ocean confirms that they compose a single fold belt despite the presence of intervening ocean. Whatever the origin of the ocean, the partition of these areas postdated their origin and was the result of the generation of the North Atlantic basins.

The Ural-Mongolia belt is very complex in structure and includes the Proterozoic (Baikalian) fold areas of Timan, Taimyr Peninsula, Yenisei Ridge, and Baikal Highland; the early Paleozoic (Caledonian) fold areas of Sayan, Altai-Salair, Central Kazakhstan, Kokchetav-Kirghizia, and Central Mongolia; the Hercynian fold areas of the Urals, Southern Tien Shan, East Kazakhstan, the Irtysh region, and South Mongolia; and the Mongolia-Okhotsk fold area of early Mesozoic age.

All these areas make up the basement of the young and vast North Turanian and West Siberian sediment-covered platforms. Between the East European and Tarim platforms, the belt is bounded by a system of deep-seated faults running through Mangyshlak south of Sultanuizdag and separating the Pamirs from the Tien Shan.

Least studied, the Arctic belt comprises the Caledonian and Hercynian fold areas, including the islands of the North American Arctic Archipelago

and probably the northern margins of the Alaskan and Chukot peninsulas. The belt has been greatly disturbed following the sinking of the Arctic basins; hence its relations with other belts is unclear. It may be a continuation of the Ural-Mongolia belt.

The Mediterranean belt is margined on the north by the Hercynian fold belt of Western Europe (Spain, Portugal, France, Southern England, Belgium, the southern FRG, the GDR, Czechoslovakia, and Southern Poland); the Paleozoic basement of Dobruja and the Scythian sediment-covered platform, which includes the Crimean plains and the Northern Caucasus; and the South Turan sediment-covered platform, which occupies the plains of Turkmenia, South Uzbekistan, and Tajikistan. Farther eastward, the Mediterranean belt is composed of the Paleozoic fold areas of the Northern Pamirs and Kun Lun and the Mesozoic fold areas of the Karakoram, the Indochina Peninsula, Malacca, and part of Kalimantan. The southern periphery of the belt includes the Hercynian fold area of Morocco, Algeria, and Tunisia in Africa. All the above areas are localized on the margins of the belt. Its central part is made up mainly of two Cenozoic geosynclinal areas, the Alpine in the west and the Indonesian in the east. The former comprises the Carpathians, the Alps, the Pyrenees, the Mediterranean coast in North Africa, the Iberian and Balkan peninsulas, the Caucasus, Asia Minor, Iran, Belujistan, and the Himalayas; the latter consists of the large and small islands of Indonesia which eastward are followed by an arc of small islands around the Banda Sea basin. The entire garland of islands of the Indonesian Archipelago is fringed by a deep-sea trench and divided by sea basins, such as Sulu and Sulavesi.

Occurring within and around the Alpine fold area, the basins of the Ligurian Sea, the Tyrrhenian Sea, the Jonian Sea, the Sea of Marmara, and the Black Sea, and the southern Caspian Sea actually form a system. In this way the Alpine area is similar to the Indonesian one.

The Circum-Pacific belt is the greatest of all fold belts. It is composed of the fold belts located between the andesite line*, which encircles the extensive ocean floor, and the edges of the neighboring platforms, the North American, South American, Antarctic, Australian, South China, China-Korea, and Siberian. The small Kolyma platform may be regarded as located inside the belt. The belt is subdivided into two major parts which are recognized by many scientists as separate segments, the Australian-Asian and American. The Australian-Asian part encompasses the Pacific coast of Asia, together with the fringing islands; eastern Australia and New Guinea; the islands of Melanesia; and New Zealand. This part of the belt includes the late Proterozoic fold area of Adelaide in Australia, the Paleozoic fold area of East Australia, the fold area of Sikhote-Alin, and the Cenozoic fold areas, the Kamchatka-Koryak and Sakhalin, and also those of the islands of Japan, the Philippines, New Guinea, and New Zealand.

The Verkhoyansk fold area is in Eastern Siberia, between the Siberian and Kolyma platforms. Its fold structures were formed late in the Jurassic—early in the Cretaceous. Therefore, it is Mesozoic (Cimmerian) in age. This

* The andesite line is the boundary between the area of andesitic lavas on the margins of the Pacific and the interior of the ocean, where basaltic lavas predominate.

area should be considered an outgrowth from the Circum-Pacific belt that intervenes between the two ancient platforms.

The youngest Cenozoic geosynclinal areas occur as extensive island arcs: the Aleutian, Kuril, Bonin, Mariana, Ryukyu, Fiji, and Tonga-Kermadek, and those of West Melanesia, the Solomon Islands, and New Hebrides.

Several narrow deep-sea trenches run along the chain of the East Asian island arcs, separating them from the flat Pacific floor. Similar trenches (Philippines Trench, Nanai Trench, and that near Ryukyu Islands) occur between some island arcs and interisland sea basins.

The island arc areas also embrace the deep basins of a number of Asian marginal seas: the Bering Sea, the Sea of Okhotsk, the Sea of Japan, the East China Sea, the Philippine Sea, the New Guinea Sea, the Coral Sea, the Solomon Sea, the Tasman Sea, and the Fiji Sea.

Island arcs are made up of one or two parallel garlands of the leading and trailing arcs with a narrow intervening trough. The trailing arc often consists of volcanoes, while the leading arc may be lacking in volcanic manifestations. The volcanic products in island arcs are andesite, andesite-basalt, and more acid rocks.

Island arcs are underlain by a fairly thick crust, thicker than beneath the oceans. Although not always persistent, the granitic-metamorphic layer is often present in the crust. Therefore, the earth's crust under arcs approaches that of the continental type and may be called transitional. From geophysical evidence, the crust beneath interisland basins and deeps is made up of a basaltic layer covered by a thick pile of sediment (up to 3-4 kilometers). Many of the interisland sea basins have a rugged surface and are composed of areas with a flat, occasionally shattered floor at depths of 3 000 to 5 000 meters, and of intervening ridges.

Island arcs, trenches, and deeps apparently combine to form present-day geosynclinal areas with their deep troughs and narrow upfaulted elevations at an early stage of development.

The American stretch of the Circum-Pacific belt includes the Paleozoic fold area of Puna in Bolivia. According to new data obtained by a Brazilian scientist F. Almeida, this Paleozoic area should include a long strip of the Andes, from the Chilean boundary on the south to Columbia on the north. The Rockies from Alaska to Mexico belong to the Mesozoic area. The Cenozoic areas embrace the Coast Ranges of Canada and the USA, the Californian Peninsula, the Central American Istmus south of Yucatan, the Andes of Venezuela, Cuba, Haiti, and the Caribbean island arcs with their accompanying trenches. The Caribbean Sea basins are very similar to those of the marginal seas in the Asian and Australian stretches of the Circum-Pacific belt, being also fringed by island arcs and trenches. Like the Indonesian islands, these arcs appear to represent a modern geosynclinal area still under development. The Southern Andes of Chile and Tierra del Fuego can be referred to as the Cenozoic area. Their extension is the arc of the South Sandwich Islands which, together with a trench, borders the deep of the Scott Sea. Like the Caribbean arc, this area may be classified as a present-day geosynclinal system. Likewise the Caribbean arc, which is related in trend to the Venezuelan Andes, the South Sandwich Islands parallel the Tierra del Fuego and Graham land in the Antarctica. Although geographical-

ly the Caribbean Sea, its island arc, and the arc of the South Sandwich Islands are within the Atlantic Ocean, they are tectonically associated with the Circum-Pacific belt.

On the whole, the Circum-Pacific belt is asymmetrical: on the periphery of the deep-ocean part of the Pacific, the youngest (present-day and Cenozoic) geosynclinal areas occur; farther outward are the Mesozoic, and on its outer margins the Paleozoic and the Baikalide geosynclinal areas in Adelaide, Australia, and in Catasia, China. All the five major belts, the principal of which appears to be the Circum-Pacific belt, are closely associated with one another and form a single world-wide system. The Mediterranean belt may be considered a huge outgrowth from the Circum-Pacific one; it forms a giant fan in the area of the Indonesian islands. The Atlantic and Ural-Mongolia belts are isolated from the Circum-Pacific belt by fault systems, the former within Central America and the latter in the Far East, west of the Sikhote-Alin and the Amur River area. The Circum-Pacific belt is thus the principal unit of the earth's surface, the other belts being essentially outgrowths from it.

IV

THE STRUCTURE AND HISTORY OF GEOSYNCLINAL FOLD AREAS

THE STUDY OF GEOSYNCLINES

Before examining the entire history of major and minor fold belts, it is first necessary to discuss in more detail the structure and history of their constituent geosynclinal fold areas. We know now that the areas composing a fold belt are of different ages, but basically similar in structure and evolution. Let us consider what they have in common.

Geosynclinal troughs, or geosynclines, are major structural elements of geosynclinal areas. Their development, which is now considered the fundamental process of continental crust build-up, is closely associated with folding, igneous activity, and metamorphism.

What does the term "geosyncline" mean?

At the outset, geosynclines ("ge" is the Greek for the earth and "sinclino" for downwarp) meant areas or strips of the earth's crust that were distinguished from the neighboring ones by a stronger downwarping throughout the geologically vast stretch of time, resulting in a much thicker pile of sediment. The term "geosynclinal" (now obsolete as a noun) was first used in 1873 by J. Dana, who singled out a Paleozoic geosyncline in the Appalachians. Little was known about geosynclines for a long time, and it was not until 1900 that Professor E. Haug of the Sorbonne proved that geosynclines are widespread and play a tremendous role in the earth's history. E. Haug divided the entire surface of the continents into geosynclines and continental platforms. He found that folded mountain ranges rise at the sites of geosynclines. Since then geosynclines have been considered to be the places of their origin, and a new subdivision of geology has emerged, the study of geosynclines.

Early in this century, scientists became aware of the extremely complex geology of the Alps. Here, a number of comparatively thin sheets of strongly folded rocks were detached from their original place of origin, shoved against one another, and displaced for great distances.

The resulting overthrust sheets were generated by the processes restricted to the geosyncline that once existed in the area now occupied by the Alps. Taking the Alps as a pattern, L. Kober (1921) determined two stages in the evolution of geosynclines: downwarping and mountain building, or orogenesis. He also examined the role of median masses intervening geosynclines, that is, areas between troughs. He believed that these masses acted as rams exerting pressure on geosynclines to squeeze out of them overthrust sheets of sedimentary rocks.

Many major features of geosyncline evolution were then discerned by H. Stille (1927), the famous German tectonist. He was the first to show that the generation and development of a geosyncline is a regular process; it begins with the sagging of the earth's crust and accumulation of thick sedimentary and extrusive series, and ends up with their folding.

He subdivided the earth's history into protracted tectonic cycles. Each cycle involves the formation and development of geosynclines and the generation of fold structures which marks the end of the geosynclinal process. Stille attributed folding to the evolution of geosynclines and believed that folding took place during short episodes simultaneously all over the world. However, that the folding episodes were synchronous was not confirmed. On the contrary, they were found to have occurred in different fold areas at widely different times.

The leading role in elaborating the geosyncline theory belongs to A.D. Arkhangel'sky and N.S. Shatsky. Analyzing the enormous body of information on the geology of the Soviet Union available after the geologic surveys of its vast territories in the 1930's, they found that the geosynclinal process involved not only individual geosynclinal troughs, but also vast tracts of the earth's surface, geosynclinal areas. Since then many other Soviet tectonists have contributed much to this theory. Thus, while studying the geologic history of the Caucasus, V.V. Beloussov first applied the method of analyzing facies and thicknesses of sediments. He concluded that in the course of the geosynclinal process the geosyncline is transformed from the zone of maximum downwarp into that of maximum upheaval after orogenesis. He later developed a coherent theory of the geosynclinal process, which considered it the result of undulatory oscillations of the earth's crust.

Studying the tectonics of the Urals and Tien Shan, A.V. Peive discovered deep-seated faults, the basic type of faults. They cut through the entire earth's crust and control crustal fold and block structures. In particular, deep-seated faults delineate geosynclinal troughs.

Shatsky's study of geologic formations has played an important part in the elaboration of the geosyncline theory. He described geosynclinal formations and distinguished them from platform formations.

Analysis of geologic formations opens new possibilities for explaining the history of fold areas and makes it possible to establish the distribution of the various types of formations and the succession of sedimentary and volcanic rock complexes.

Having studied the formations and structural types of geosynclinal areas, in 1963 this writer distinguished two basic types of structure of a geosynclinal area and, accordingly, two stages in its development: the main, or geosynclinal, and the final, or orogenic. The volcanism, as well as the igneous activ-

ity in general, of the geosynclinal area is associated precisely with these two stages.

A.A. Bogdanov, V.V. Beloussov, A.V. Peive, A.L. Yanshin, V. E. Khain, Yu. A. Kosygin, and others have offered many clues to the history of geosynclines. Yu.A. Bilibin, Yu.A. Kuznetsov, and many other geologists have dealt with the underlying relations of geosynclinal processes with igneous activity and mineral formation.

Therefore, following the detailed investigations over the territory of the USSR, the study of geosynclines has grown into a well-founded theory of the geosynclinal development of the earth's crust. General systematic features of geosynclinal areas were outlined, and their basic lines of evolution were found to be common.

THE STRUCTURE OF GEOSYNCLINAL FOLD AREAS

Geosynclinal fold areas are the parts of fold belts where the formation of geosynclines, their filling with sediments, and transformation into a fold area took place at one time. The time interval from geosyncline formation to the cessation of folding is the "tectonic cycle".

Common structural elements are singled out in all geosynclinal areas, as are similar stages and phases in their evolution. These elements are primarily geosynclinal troughs. From several to great many troughs may occur within a geosynclinal area. All of them are identically aligned, that is, elongated in one direction, and are bounded by systems of deep-seated faults. Such faults also cut across the troughs themselves, which are filled with sedimentary and volcanic rocks.

Geosynclinal troughs are interspersed with remnants of the crust in which they originated. This crust underlies more or less extensive areas—median masses—bounded by faults and generally elongated parallel to geosynclinal troughs.

Two basic types of crust exist in which trough systems originated. It may be of the ocean type and thus be made up of the basaltic (melanocratic) layer covered by sedimentary rocks; or the geosynclinal troughs may develop in the continent-type crust that is broken up and pushed aside. In this case the crust consists of older folded and metamorphosed series and igneous rocks from under which, at the bottom of the troughs, may protrude parts of the crustal basaltic layer and of the mantle.

In geosynclinal troughs, some of the marginal or centrally lying blocks are uplifted to generate geanticlines. This process may involve the margins of the adjoining masses or those of the entire mass provided it is small and is between two geosynclinal troughs. When a part of a trough or the margin of a mass is greatly upheaved, a large uplift emerges that may later be transformed into a complex anticlinorium. At the same time, sedimentary and volcanic rocks that fill the trough between these uplifts or between its sides are involved in systems of more or less complex folds. On the whole, the trough disturbed by folds becomes a synclinorium.

Another major structural element of a fold area is a median mass. It contains the metamorphic basement made up of older rocks. In major fold belts, these are mostly of a late Proterozoic age. The basement of the median mass may be exposed, but is for the most part overlain by sedimentary and volcanic series. The resulting cover is composed of rocks of the same age as those filling the geosynclinal troughs, but thin and of completely different composition. These are clayey rocks, sandstones, limestones, dolomites, and some volcanic rocks constituting the platform-type complex; hence, the sedimentary cover resembles in structure small areas of platforms. However, it may be more disturbed than on platforms, forming step-faulted blocks and local folds above faults. The cover is frequently intruded by granites and other igneous rocks associated with the magmatism in the neighboring geosynclinal troughs.

The third basic element of a geosynclinal area is a system of orogenic basins. They appear at the very end of the geosynclinal cycle, after the folding of the sedimentary and volcanic rocks that fill geosynclinal troughs. In many places the folding is known to have progressed through a number of episodes, but the final one was always the most important. This episode was followed by new downwarping which created a system of troughs belonging to the new system of depressions—that of the orogenic stage. They formed within both median masses, which are topped by the sedimentary cover, and folded geosynclinal troughs. Orogenic troughs are of various shapes—elongate, oval, or simply narrow grabens. Foredeeps constitute a special subdivision, appearing along the boundary of a geosynclinal area with a platform.

Orogenic troughs are interspersed with large or small mountain areas, which grow while the troughs are subsiding. The troughs are filled with sediments supplied by these areas. Such sediments, composed of conglomerates, gravelstones, and sandstones derived from the wearing down of mountains, are called molasse, and the totality of the molasse facies filling an orogenic trough is termed orogenic, or molasse, complex.

Thus any geosynclinal area is made up of three distinctive units. The lower unit is made up of the foundation in which a system of geosynclinal troughs was initiated. It consists of basic igneous rocks underlying the ocean floor, or of the folded metamorphic rock complex that composes median masses. The middle unit comprises sedimentary, volcanic, and plutonic rocks filling geosynclinal troughs and forming the cover of median masses. The upper unit is made up of formations filling orogenic troughs and occasionally blanketing the sides of growing mountain areas.

In studying any geosynclinal area, these units can be recognized easily. They correspond to the major stages in its evolution. More precisely, the foundation corresponds to some older period in the development of the area, while the two other units, called the main geosynclinal and orogenic, correspond to the other two stages.

Therefore, by analyzing the tectonic structure of a fold area and by dating its structural units, it is easy to establish the major stages of its tectonic cycle.

The structural unit principle was the basis for several tectonic maps, including the Tectonic Map of the USSR, edited by N.S. Shatsky, International Tectonic Map of Europe, edited by N.S. Shatsky and

A.A. Bogdanov, Tectonic Map of Eurasia, edited by A.L. Yanshin, Tectonic Map of Arctica, edited by Yu.M. Pushcharovsky, Tectonic Map of the Pacific Ocean and Its Coasts edited by Yu.M. Pushcharovsky, G.B. Udintsev, and others.

AN OUTLINE HISTORY OF GEOSYNCLINAL AREAS

Now that we have described the general structure of geosynclinal areas, we can familiarize the reader with their history, which is known to consist of two stages: the main and the orogenic. We shall discuss these separately and then focus our attention on the origins of sedimentary and volcanic formations, intrusive igneous rocks, and mineral deposits.

Main Stage

The formative stage of a geosynclinal area is invariably associated with a system of faults cutting through the foundation. Some of its blocks, bounded by faults, then subside to form geosynclinal troughs, while the others in-

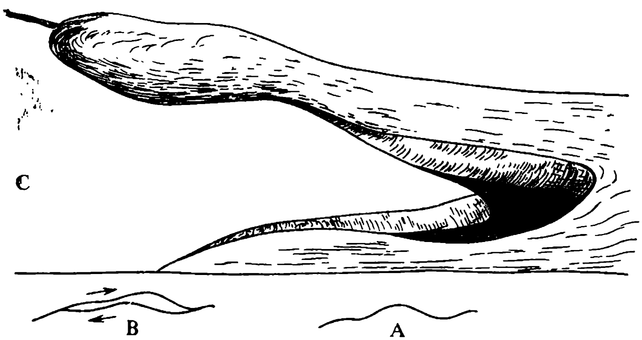


Fig. 11. **Formation of breaks in the earth's crust by lateral motion on a curvilinear fault line (*A* and *B*).**

In some regions, gashes form in the crust, and its deep parts or the surface of the mantle protrude through them. In the other regions, tremendous stresses develop, and blocks of the earth's crust are shoved against the opposite flank of the fault. A sketch *C* illustrates this process

between remain elevated to become median masses. The diverging and converging faults in the crust usually constitute an elongated system, which is caused by crustal block movements.

The relationship between the faults and the large crustal blocks suggests that the motion may be vertical or horizontal over widely differing distances. When it is protracted, zones of shattering, friction, and folding originate along faults. Horizontal movements along somewhat curvilinear fault lines may produce considerable gaps in the earth's crust. And if the faults are deep seated, cutting into the mantle, not only the basaltic layer, but also part of the upper mantle may be exposed between them. The same may happen if crustal blocks are pushed aside (Fig. 11).

This is now observed in many fault, or rift, zones of the earth's crust such as in the Red Sea, where, according to geophysical evidence, the sedimentary sequence is undoubtedly underlain by rocks of the basaltic layer while in the middle of the trough the fault zones may show mantle protrusions

Within the mid-oceanic ridges, the earth's crust, which is represented by the basaltic layer, moves in opposite directions, and ultrabasic rocks of the upper mantle protrude.

Most important features of geosynclinal trough systems are deep-seated fault systems and the areas that are not underlain by the continental crust. Later in the development of true geosynclinal systems, the deep-seated rocks of the basaltic layer or even mantle may be forced along the faults to the earth's surface by intense crustal movements to form extensive overthrust sheets and nappes.

The faulting along troughs during their early formative stages is accompanied by more or less vigorous igneous activity. Faults are lower-pressure passageways for the rise of the mantle-derived basaltic magma. The magmatic melt in the asthenosphere tends to move from the higher-pressure zone to the lower-pressure zone, that is, upward. Rising to the surface through faults within geosynclinal troughs, the magma serves as the source of voluminous volcanic outpourings of diabase, spilite, basalt, and other basic rocks. Underwater eruptions are distinguished by interaction of a hot basaltic melt, whose temperature is perhaps near 1 000 °C, with water. This results in explosions beneath the water to produce finely broken tuff and siliceous-tuffaceous and many other volcanic-clastic rocks. Diabase lavas are associated with gabbro and gabbro-diabase intrusions which worked their way from below upward through faults into the upper crust, where they slowly consolidate.

The geosynclinal trough formed by the subsidence along faults is seen on the earth's surface as a very deep and narrow submerged depression filled with marine sediments. Extrusive rocks were also erupted mainly from submarine volcanoes whose chains follow fault lines. Underwater eruptions with their tremendous explosions produce an alternation of lavas, tuffs, and ejecta (Fig. 12).

Apart from basic volcanic and intrusive rocks, generally small elongated bodies of ultrabasic rocks altered to serpentinite invade along some of the deep-seated faults. These rocks were expelled from, and squeezed out of, the mantle as solid or viscous plastic masses.

Therefore, from the outset geosynclinal troughs have been directly connected with the mantle and its escapes, magmatic melts of basic (basaltic) composition.

Marine sediments that fill geosynclinal troughs are generally composed of clayey and subordinate sandstone strata. Also present are tuffs, tuff breccias, and other volcanic products, such as rather common siliceous-clayey rocks and silicilites and jaspers, purely siliceous sediments. These last precipitate from SiO_2-rich water solutions which are of volcanic origin and seep on to the surface as hot springs called fumaroles. Limestones, as well as other carbonate rocks, are, as a rule, completely subordinate; they occur as layers and lenses enclosed in other rocks, or make up bioherms, structures of the reef type built up of skeletons of the various organisms: corals, moluscs, the calcareous algae lithothamnia, bryozoans, and many others.

Two basic types of geosynclinal troughs are distinguished: the terrigenous, with the predominance of clayey-sandy rocks, and the volcanogenic, with the predominance of basic volcanics. These types are both assigned to geo-

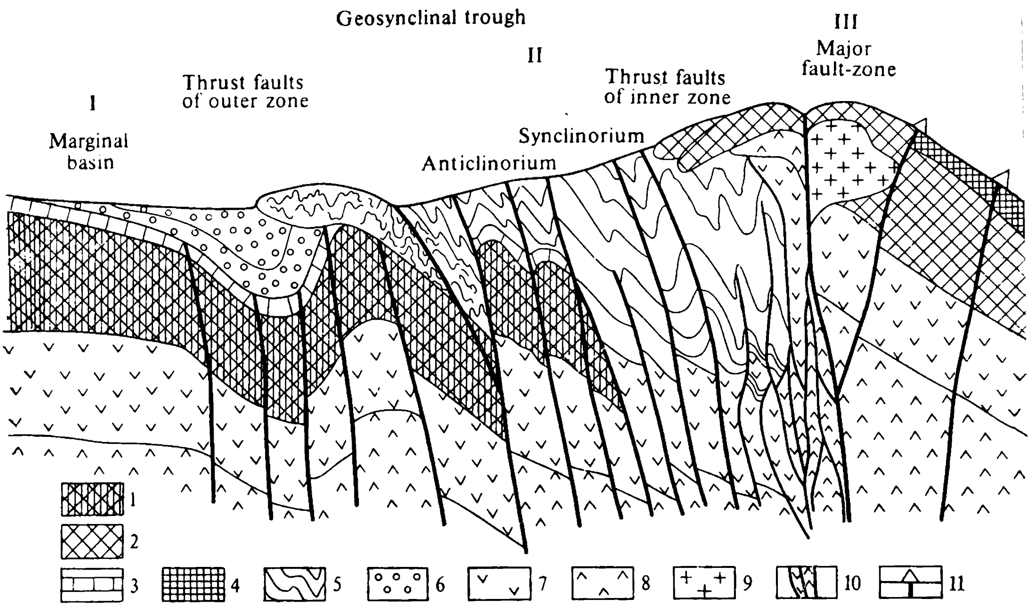


Fig. 12. A cross-section of major structural units of a geosynclinal fold area:

I — marginal basin;
II — geosynclinal trough transformed into synclinorium;
III — upfaulted block of median mass, which is core of anticlinorium;
IV — median mass;
V — intermontane basin;
1 — basement of platform;
2 — basement of median mass;
3 — sedimentary cover of platform;

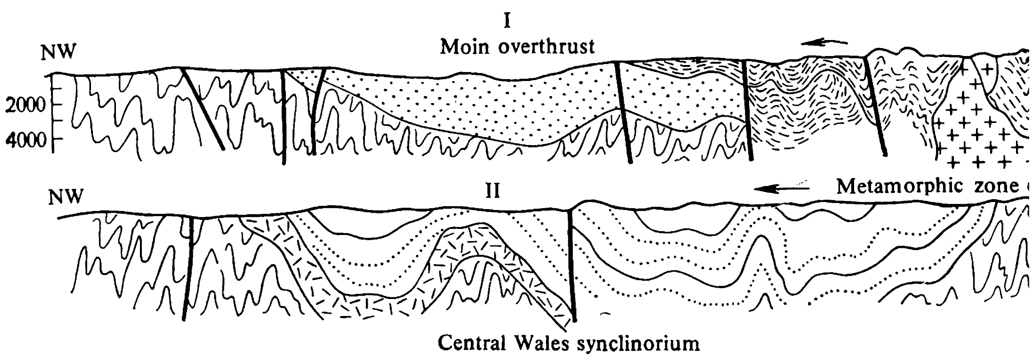
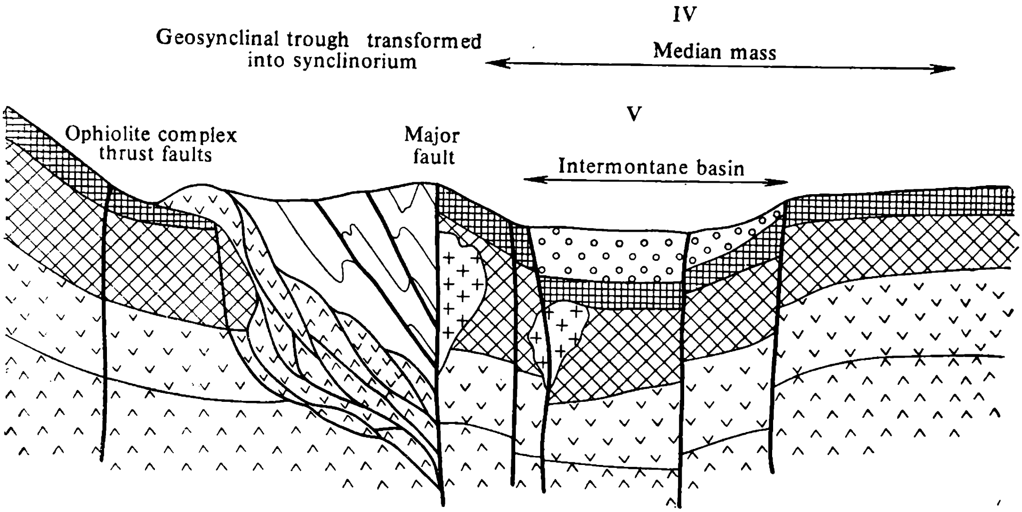
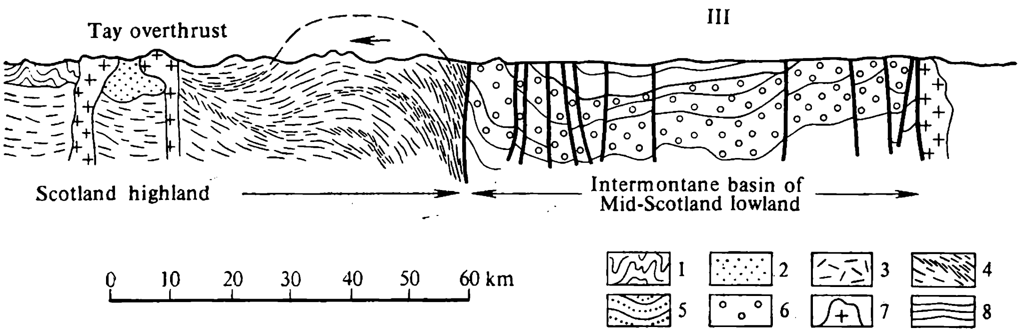


Fig. 13. The complex fold-thrust structure of the geosynclinal trough of the Scotlan montane trough of the orogenic stage of the Great Britain fold area of Caledonian age (*III* J. Stubblefield):

1 — Lewisian made up of metamorphic rocks and gneisses, and gneisses of Anglesey Peninsula of late Proterozoic age;
2 — Torridonian sandstone (upper Proterozoic sedimentary cover);
3 — terrestrial sediments and acid extrusive rocks of sedimentary cover;
4 — Moinian and Dalradian consisting of schists and extrusive rocks (late Proterozoic to Middle Cambrian in age);



4 — sedimentary cover of median mass;
5 — geosynclinal rock complex containing extrusive rocks;
6 — molasse of marginal or intermontane basin;
7 — basaltic layer of earth's crust;
8 — upper mantle;
9 — granite intrusion;
10 — fault-zone;
11 — volcano



ighlands (*I*), the simpler structure of the trough of Central Wales (*II*), and the inter-
ıfter the sections to the Tectonic Map of Great Britain compiled by F. Dunning and

main geosynclinal column has been folded and thrusted northward; surfaces of thrust faults are shown by heavy lines;
5 — geosynclinal column composed of Cambrian, Ordovician, and Lower Silurian rocks found in Central Wales trough initiated later than Scotland trough early in Paleozoic;
6 — Silurian rocks and Lower Sandstone of Devonian age — shallow-water and molasse complex filling orogenic basin;
7 — Caledonian intrusions;
8 — sediments of platform (Devonian to Carboniferous)

synclines proper, eugeosynclines. Early in their development, sedimentary formations and volcanic and sedimentary series in some geosynclinal troughs are 5-10 or more kilometers thick (Fig. 13).

An ophiolite complex is characteristic of volcanogenic troughs, consisting of clayey-sandy rocks and jasper, diabase outpourings and masses of gabbro and ultrabasic rocks altered to serpentinite. The ophiolite complex is found in the geosynclinal areas of quite different ages: Paleozoic, Mesozoic, and most recent, such as the Alps, Caucasus, and Sagross in Iran.

Subsequently, the crustal movements that constantly accompany the formation of geosynclinal troughs more or less intensely deform the contained strata. These are greatly raised and folded in some places where geanticlines grow, the folding being strong on their sides and on the margins of the troughs. These processes are attributed to infrequent folding episodes, crustal movement pulses.

Within some troughs fairly voluminous underlying rock masses are forced to move on the bounding fault planes; they are shoved against the adjoining areas to produce overthrust sheets or nappes (Fig. 14). Such overthrust sheets may contain rocks of the ophiolite complex, extensive masses of gabbroic rocks and serpentinites derived from upper mantle's peridotites, and rocks composed of a serpentine matrix with blocks and smaller fragments of gabbro, diabase, schist, gneiss, and some limestones of different ages. These rocks are called mélange, that is, a medley (they are also called olistostrome). They may have piled up following the substantial displacement of the serpentinites that were squeezed out from below and captured fragments of other rocks on their way upward along faults.

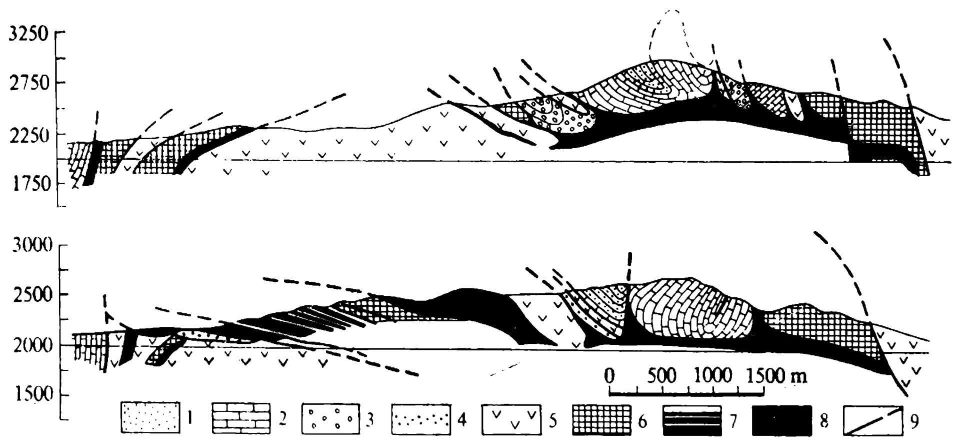


Fig. 14. Geologic cross-sections of the Shakhdag Ridge of the Lesser Caucasus (prepared by A.L. Knipper and Yu.L. Kastanyan):

1 — Paleogene flysch;
2 — Upper Cretaceous limestone or marl;
3 and *4* — red or green conglomerate or sandstone of lowermost Upper Cretaceous;
5 — volcanic-sedimentary series of lowermost Upper Cretaceous;
6 — gabbro or gabbro-amphibolite;
7 — alternating gabbro, pyroxenite, and serpentinite (banded stratified complex);
8 — ultrabasic rock (serpentinite);
9 — fault

Separate uplifts within the troughs gradually expand, with the resulting changes in the mode of sedimentation and in the composition of volcanic products. More acid andesite begins to predominate over diabase, and diorite and granodiorite intrusives appear instead of gabbro ones.

These processes usually mark the transition from the initial to the mature stage of trough evolution. The separate uplifts grow up and form underwater ridges whose tops rise above sea level as islands. Such ridges are called cordilleras. As they are eroded, coarse sandstone and even some conglomerate are laid down around them. On the whole, the system of geosynclinal troughs is at this time a sea crossed by archipelagoes of more or less vast islands, including cordilleras.

Crustal movements affect folding of cordilleran sides, which may be subsequently raised above sea level, worn down, and then subsided again. And after subsidence, the partly eroded folds are unconformably overlain by new sedimentary layers. This helps date the folding, which perhaps took place here before the deposition of the unconformably overlying layers, but after the deposition of the folded layers.

In the mature stage, the troughs are often filled with rythmic sandy-clayey deposits; these are flysch and flyschlike series, marly formations, and bedded carbonates. Volcanic rocks vary in thickness from very thick andesitic lava flows and tuffs through thin members or are completely absent.

During this stage the highly variable total thickness of sedimentary and volcanic rocks often reaches a few thousand meters and rather frequently 5 000-6 000 meters (Fig. 15).

It is worth mentioning that in addition to the system of troughs whose age is the same as that of a geosynclinal area, there exist much younger geosynclinal troughs. A most striking example is the Alpine fold area where major geosynclinal troughs originated either at the end of the Triassic or at the beginning of the Jurassic. Troughs formed early or even late in the Early Cretaceous (in the Hauterivian or Albian) have been found in the Caucasus and the Carpathians. Interestingly, they evolved fast, with the final folding between late in the Eocene and the end of the Oligocene. The initial stage in the evolution of the younger troughs characterized by diabase volcanism was very short; the mature stage was longer, and only andesitic volcanism, if at all, manifested itself at that time (Fig. 16).

At the end of the main stage in the geosynclinal cycle, great volumes of acid granitic magma intrude and crystallize to form plutons of granodiorite, plagiogranite, and similar rocks.

The stage is completed with a folding episode that results in an intense crumpling of all sedimentary and volcanic series. The troughs close up, that is, sediments cease to accumulate in them and they rise above sea level nearly throughout their extent. They include sedimentary and volcanic series, as well as the flanks of geosynclinal troughs which become generally invaded by numerous basic and acid intrusives.

According to Beloussov, the process of closing up geosynclinal troughs and their general uplift is an inversion of the tectonic regime. In fact, it relates to general uplift, but highest rises at the place of lowest saggings are not observed, that is, no inversion really takes place. Only some of the growing geanticlines rise highly, these being formed earlier, at the beginning or in the

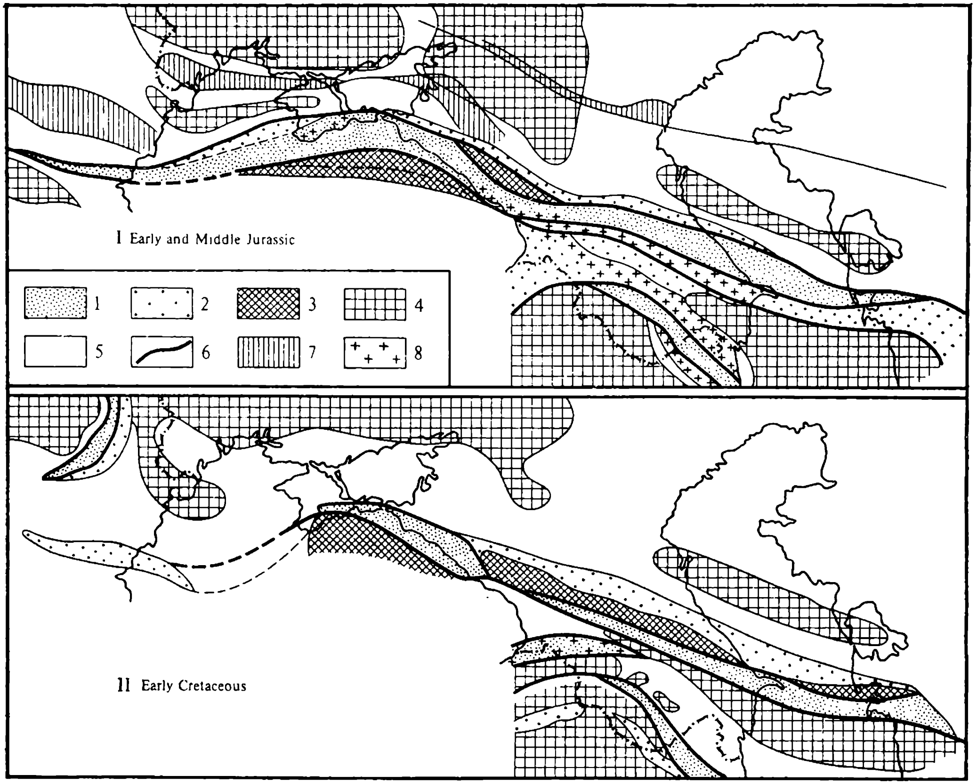


Fig. 15. A paleogeographic map showing the Caucasus geosynclinal area in different phases of its geosynclinal cycle:

I — schematic map showing paleogeography of Caucasus early in Jurassic (early phase of development);
II — schematic map showing paleogeography of Caucasus in Early Cretaceous time (mature phase of development);
1 — geosynclinal trough;
2 — trough filled with thin sediment;
3 — geanticline uplift;
4 — area of median mass or platform raised above sea level;
5 — area of median mass or platform covered by shallow sea;
6 — fault;
7 — grabenlike trough;
8 — volcanic manifestations

middle of the main stage. Huge upheaval and inversion involve only parts of the previous trough, generally at its edge. Sometimes the upheaval begins outside the trough and then grows higher and wider, gradually involving its margin or even its central part.

What happens during the main stage in the median masses that are next to geosynclinal troughs or occur between them?

These masses usually also become submerged, and sediments accumulate on their surface. The resulting bedded column is composed of sandstones, thick limestones and dolomites, clayey rocks alternating with sandstones, and lava flows and tuffs of basic and more often andesitic composition. All rocks change little along the strike and are flat-lying, thus forming the sedimentary cover of the masses. At places the median masses become broken up into blocks, with sedimentary layers of their cover bent and folded near

faults. These layers are much thinner than those of the same age in geosynclinal troughs. They are locally folded as a result of faulting, but on the whole less disturbed. Within the median masses, sedimentary rocks may enclose intrusive bodies of the same age, and basic and more often granodioritic bodies of the same composition as those in the troughs.

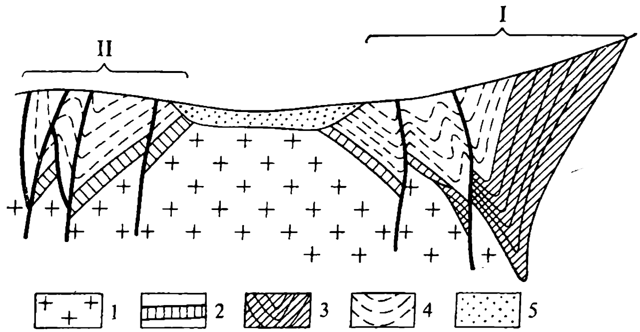


Fig. 16. Schematic presentation of differences between early (*I*) and late (*II*) troughs as exemplified by the Alpine fold area of the Caucasus:

1 — metamorphic basement of median mass;
2 — sedimentary cover of median mass (Pz);
3 — geosynclinal complex of early phase ($J_1 J_{1-2}$);
4 — geosynclinal rock complex of late phase ($J_3 K_1 K_2 P$);
5 — intermontane trough of orogenic stage

Much more strongly deformed are those parts of the masses that adjoin geosynclinal troughs, or narrow intervening masses. They undergo substantial upheaval and are thus transformed into geanticlines and systems of uplifts already rapidly growing in the orogenic stage.

Orogenic Stage

Subsequent to uplifts at the close of the main stage, a new type of depressions—orogenic troughs—begin to subside. They form at the same time as the growth of orogenic uplifts, as if they compensate the gross upheaval. Orogenic troughs are for the most part initiated on the surface of median masses or on that of their sedimentary cover. In some areas they inherit the most downwarped parts of geosynclinal troughs, but this is rather an exception to the rule (Fig. 17). An example of the above is the Eastern Carpathians.

Foredeeps located on the margins of platforms are the special widely known type of orogenic troughs (Fig. 18). Orogenic troughs are filled with a thick pile of sedimentary and volcanic rocks. On the margins of troughs and along the fault systems these rocks are folded. We can often see in young orogenic troughs magnificent volcanic cones, and sometimes even lines of volcanoes of different sizes.

Orogenic troughs undergo strong but relatively short-term downwarping. Their life is much shorter than that of geosynclinal troughs. The Upper Paleozoic (Hercynian) orogenic systems evolved from the Middle Carboniferous to the middle or the end of the Permian, that is, over 80 million years, and the Cenozoic ones from the Oligocene to the Quaternary, that is, over 28-35 million years.

Orogenic troughs are greatly affected by igneous intrusions, mainly granitic. It is at this time that big granite bodies are emplaced and solidify stretching along geosynclinal areas and forming batholiths. Granites are typical of most of the geosynclinal fold areas, but only in older, Paleozoic areas of West Europe, the Urals, Kazakhstan, the Tien Shan, and elsewhere they are

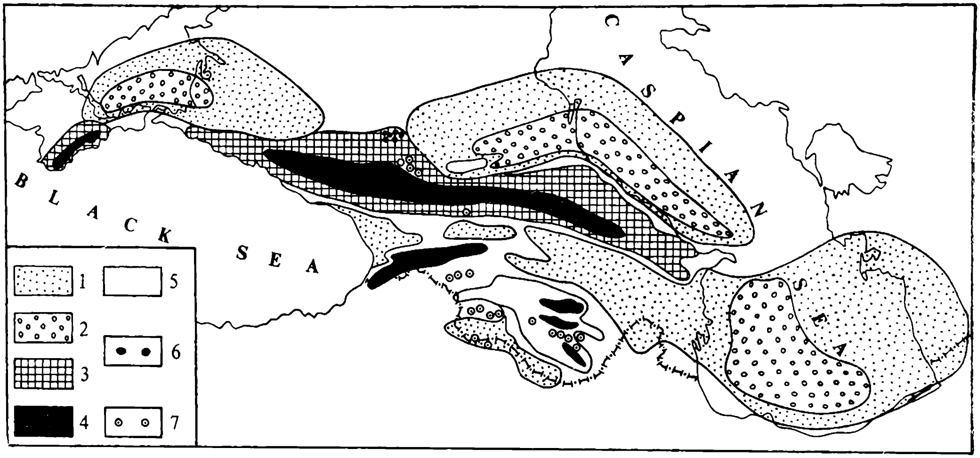


Fig. 17. A schematic map show ng structures of the orogenic stage of the Caucasus and the Crimea:

1 — intermontane or marginal basin;
2 — deepest portion of basin;
3 — orogenic uplift area (growing mountains);
4 — highest portion of mountain;
5 — side of uplift or basin;
6 — laccoliths in Northern Caucasus;
7 — major volcanoes

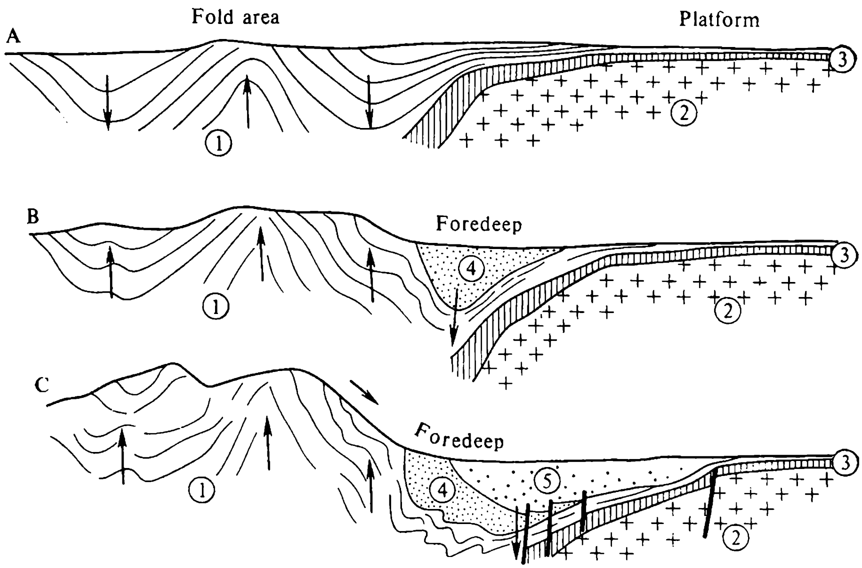


Fig. 18. Schematic presentation of the development of a foredeep (after A.A. Bogdanov):

1 — geosynclinal rock complex of fold area;
2 — basement of platform;
3 — sedimentary cover of platform;
4 — lower molasse in first phase of foredeep history;
5 — upper molasse in second stage of foredeep history (continental molasse);
A — before foredeep formation;
B — early phase;
C — late phase

exposed and are major topographic features. Batholiths are not exposed in younger geosynclinal areas—in the Caucasus, Carpathians, and Alps—but we may suppose the occurrence of deep-seated granitic batholith-type bodies as cores of mountain ranges.

The orogenic stage is also associated with folding, most frequently with its only episode at the end of the stage, though sometimes with two or three. The volcanic and sedimentary rocks that fill orogenic troughs are severely folded. At the same time, major uplifts grow to form mountain ranges interspersed with depressions.

The intense upheaval is accompanied by major overthrusting and nappe formation, with the displacements directed from the sides of uplifts toward the fringing depressions. Such a type of nappes are best known from the Lake Geneva area in the foredeep of the Alps. Here, a very complex pile was formed of Helvetian nappes brought from the Alps proper in the south and overriding the foreland molasse (Fig. 19). Members of crushed layers, which slipped down the slopes of growing uplifts, played a prominent role in the origin of these nappes.

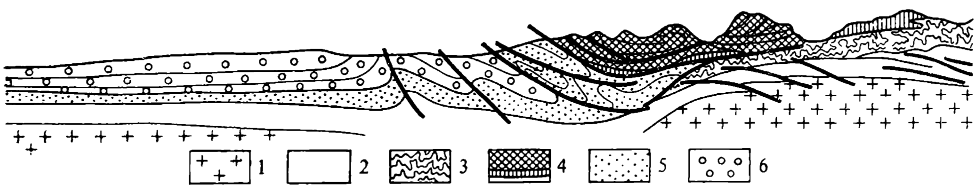


Fig. 19. Nappes of the Alpine foredeep (after A. Heim):

1 — crystalline foundation of Alps (Aar massif);
2 — Jurassic-Cretaceous sedimentary cover;
3 — Paleogene flysch;
4 — members of Paleozoic rocks (vertical shading) brought from Alps and of Mesozoic rocks, particularly flysch, shoved against flank of foredeep;
5 — molasse of Alpine foreland complicated by thrust faults;
6 — molasse Alpine foredeep

The end of the orogenic stage is marked by the cessation of anticlinal uplift growth, downwarping, and folding. Evidence for the close of these processes consists of unconformable and flat-lying sedimentaries that overlie the troughs and are not involved in their deformation. These make up a sedimentary cover and thus signify the end of the geosynclinal cycle and the formation of a platform within which all geosynclinal folds, median masses, and other structures merely compose its basement and are overlain by a sedimentary cover.

FORMATIONS OF SEDIMENTARY AND VOLCANIC SERIES OF GEOSYNCLINAL AREAS

During geologic time, various, mainly marine, sediments and volcanics accumulate in the geosynclinal area. Those deposited in geosynclinal troughs differ considerably from those in median masses or orogenic troughs. Hence

Table 3

Formations of Geosynclinal Fold Areas

Stage and phase in geosynclinal cycle	Formation of geosynclinal trough		Formation of geanticlinal uplifts
	Type of formation	Major formation	
Orogenic stage			Of weathering crust Glacial formations River valley formations
Late phase			Volcanogenic formations of volcanic sheets and cones
Early phase			Basaltic, andesitic, and liparite-dacite formation
Main stage	Flysch	Flysch with lavas and tuffs Carbonate flysch	Sandy-clayey and conglomeratic formations
Mature (late) phase		Terrigenous (sandy-clayey) flysch	
	Carbonate	Of bedded and massive limestones	Of reef limestones
	Terrigenous	Clayey-siliceous (culm) Clayey-sideritic Clayey-sandy Keratophyric-tuffolava	
	Volcanogenic	Andesitic-tuffolava Porphyritic-tuffolava	Of porphyrites and tuffs
	Terrigenous	Clayey-sandy flysch Graywacke Of shales and sandstones Tuff-siliceous Of cherty shale	Of volcanic series Of limestones (small reefs)
Early phase		Distant siliceous Jasper-shale Volcanogenic-siliceous	
	Volcanogenic	Spilitic-tuffolava Diabase-tuffolava Siliceous-diabase	

* Volcanogenic formations occur only in intermontane orogenic troughs and in very few mar

Formation of orogenic troughs		Formation of sedimentary cover of median masses
Type of formation	Major formation	
Upper molasse	Red-bed and variegated lagoonal and continental	Trachyte-andesite volcanogenic
	Liparite-dacite and porphyric volcanogenic*	
	Sandstone-conglomerate (coarse molasse) Moraine clayey-coquina Salt-bearing	Of volcanic sheets (basalts, andesites, liparites, and dacites)
Lower molasse	Coal measures Marine sandy-clayey Carbonate (bedded limestones and dolomites) Basalt-andesite*	Sandy-clayey Of bedded limestones and dolomites
		Volcanic and tuffolava andesite-basalt sheets
		Of bedded limestones and dolomites
		Clayey-sandy (terrigenous)
		Of bedded limestones and dolomites
		Clayey-sandy (terrigenous)
ginal troughs		

on the whole, the character of sedimentary and volcanic rocks, including their mineralogic composition, depends materially on the circumstances under which they were laid down.

Sedimentary and volcanic rock complexes accumulating throughout a certain time interval within a tectonic element and thus under similar tectonic conditions are combined under the term geologic formation.

The composition of a formation depends, above all, on the tectonic regime and position of a given area of the earth's surface during sedimentation. Within a geosynclinal trough, sediments were laid down in a deep sea, often with violent underwater eruptions, on the occasionally rugged floor. In an orogenic trough, the depositional environments were most frequently those of a shallow sea, lagoon, or even lake or foreland plain, with the resulting totally different sediments.

Finally, within median masses, sediments may have accumulated on the flat floor of a shallow sea or on land. At that time, those of the cover of the median mass were uniform over vast areas.

In growing mountain belts, deposition takes place only in some deep valleys or elevated lakes while divides and slopes are rapidly eroded to supply the material into the nearest plains and basins.

This determines the specific distribution pattern and composition of formations in mountain areas.

Thus the composition of formations generally reflects the tectonic aspects of their depositional environments, while the succession of the formations reflects changes in the prevailing tectonic regime. A series of formations indicates, therefore, the tectonic history of a trough, median mass, basin, or other structural element to which these formations are related.

The formations of geosynclinal areas may be classified by their tectonic position as those of geosynclinal troughs, the sedimentary cover of median masses, orogenic troughs, and geanticlinal uplifts (Table 3).

The formations of geosynclinal troughs, whose successions tell us the story of these troughs, are the most typical of geosynclinal areas. At the base lie formations marking the beginning of downwarping; higher in the section they are followed by those of the mature stage.

Volcanogenic and sandy-clayey (terrigenous) types of formations are the most common for the early stage in the evolution of a geosynclinal trough. These types either alternate, or one of them predominates while the other is subordinate.

Volcanogenic formations consist of thick piles of diabase lavas, underwater pillow lavas, volcanic explosion products—breccias and tuffs—and members and layers of clayey-sandy rocks. They are basic in composition and can be classified into two types. One of the types is chemically related to a common diabase (and basalt), the other contains more sodium. The higher sodium content is shown not only by chemical analysis, but often also by the presence of identifiable albite containing much sodium. Higher-sodium diabase is called spilite. True, many scientists refer to the excess of sodium as a secondary phenomenon resulting from its introduction soon after original rock emplacement (sodium metasomatism).

Therefore, two volcanogenic formations of basic composition (diabase and spilite) are recognized. Volcanogenic-siliceous formations containing notice-

able amounts of cherty shale, jasper, and other siliceous rocks alternating with lavas and tuffs are in some places closely associated with them.

The jasper formation is composed of members of brightly and variously colored jaspers alternating with lavas and tuffs and sedimentary rocks, such as non-persistent shales, sandstones, and limestones.

The siliceous-schist formation is similar to the jasper; dark-brown and black siliceous-tuff schists predominate in it at the expense of jaspers. "Distant siliceous formations", according to Shatsky, are specific kinds of siliceous ones; these siliceous rocks were formed very far from volcanoes by the hot solutions of volcanic origin that flowed out on to the sea bottom. That the rocks are siliceous is a characteristic feature, but no eruption products proper are present.

The sandy-clayey formation of the early geosynclinal phase consists, as a rule, of dark (gray, brown, black, and green) shales intercalated with sandstones. In many geosynclinal troughs, these shale formations are extremely thick. Either clayey rocks or an alternation of sandstones and clayey rocks predominate in them. In some regions, their thickness reaches several kilometers, as in the Caucasus, where that of the shale formation of Jurassic age is 6 to 8 kilometers.

In the Paleozoic geosynclinal areas, clayey formations (which contain graptolite impressions and generally consist of alternating clayey rocks, sandstones, and occasional siliceous members) and graywacke formations (which are composed of graywacke and shale) are thick and widespread. Graywacke is a sandstone made up of poorly sorted (small fragments predominate) products of erosion of volcanic rocks. They are highly characteristic of Late Cambrian and Paleozoic geosynclinal troughs.

The quite peculiar siliceous-diabase formation accumulates early in the evolution of a geosynclinal trough. It contains thick cherty shales, frequently reddish colored, more or less thick diabase flows, and tuffs. These rocks are rather frequently invaded by ultrabasic intrusions transformed into serpentinites, which occur as elongated bodies, some of them very narrow, restricted to faults.

Cherty shale is marine sediment, and diabase, spilite, and tuff are underwater volcanic products. The sediments were deposited on the floor underlain by the oceanic crust, that is, directly on the basaltic layer of the thin earth's crust, while ultrabasic rocks invaded from the mantle through faults. A.V. Peive has recently concentrated on the wide distribution and other features of this association. He has concluded that early-stage geosynclinal troughs developed in the oceanic crust.

The mature geosynclinal phase is also characterized by volcanogenic, sandy-clayey, and carbonate formations.

The volcanogenic formations are richer in silica and are of intermediate, that is, andesitic composition. They are made up of thick andesitic or porphyritic lavas * and their tuffs, and breccias of the same composition. Intermediate volcanogenic formations can also be divided into two rock

* Porphyrite is identical in composition with andesite, but has a porphyric texture and is more common in the Mesozoic, Paleozoic, and Precambrian.

types differing in chemical composition: andesite and porphyrite, on the one hand, and keratophyres containing albite (alkalic rocks), on the other.

Formations are also widespread, particularly in Paleozoic geosynclinal areas, of dark-gray or greenish shales intercalated with members and layers of siltstones and sandstones. In younger fold areas, clayey formations occur with layers and nodules of siderite. The margins of some of geosynclinal troughs are underlain by clayey coal measures of no economic value because their coal is non-persistent and ashy. A formation of clayey-siliceous rocks is also known; it is called culm in Western Europe and is restricted to the Lower Carboniferous.

Carbonate formations in geosynclinal troughs consist mostly of bedded limestones and dolomites, subordinate reef masses, and a marl-limestone formation. They are variously intercalated with layers and members of shales, sandstones, and volcanic rocks.

Extremely specific are flysch formations, which are composed of rigid rhythms of sandstone, shale, and occasionally limestone beds. Traces of erosion are often seen at the base of a rhythm. The above-lying sediments is generally the coarsest (sandstone), and then follows finer sandstone. These constitute the first element of the rhythm. It is overlain by the second element made up of shale and carbonate beds. The origin and circumstances under which flysch accumulates is specially dealt with in the literature. We only mention here that flysch formations attain great thicknesses and in some places are intercalated with members of sandstones and layers of limestones and, occasionally, volcanic rocks. Flysch formations are constantly present in the geosynclinal troughs of the Alpine fold area of Europe, Asia, and North Africa, and of the young fold areas of America. They are most frequently of Cretaceous and Paleogene age, less frequently of Jurassic age.

There are three types of flysch formations: terrigenous (sandy-clayey) flysch, carbonate flysch, and tuffaceous flysch. They all are highly characteristic of geosynclinal areas. True flysch was never found on platforms, though sequences very similar to it were observed in orogenic troughs.

On the margins of geosynclinal troughs and within geanticlines in their interior, rock formations become thinner, and coarser sandy material accumulates. Many geanticlines are aproned with sandstones and conglomerates very thick in some regions. Along with conglomerates, limestone reefs are characteristic of geanticlines. These reefs are formed of reef-building organisms, mainly of calcareous algae, corals, bryozoans, brachiopods, and others. They occasionally fringe anticlines and synclines, because they grow on the rising sea floor and at shallow depths.

The formations of the median mass sedimentary cover differ greatly from those of geosynclinal troughs. These platform-type formations are made up of generally persistent and thin layers of quartz and polymictic sandstones with glauconite, limestones and marls, and less frequently clayey rocks. Andesitic and basaltic lavas and tuffs also occur. It should be noted that the formations composing the sedimentary cover of median masses often lie within geosynclinal troughs at the base of the geosynclinal column. This cover was formed before geosynclinal downwarping. In discerning the history of a given area, the recognition of the sedimentary cover under the geosynclinal column is of paramount importance.

The formations of all the types of orogenic troughs have much in common. Volcanic and sedimentary formations are both found in them, but no volcanic formations are generally present in foredeeps.

Molasse formations are the most typical of orogenic troughs. They consist of thick conglomerates and sandstones intercalated with members of shales, or of red beds and variegated sandstones and clayey rocks. There occur some layers of gypsum, marl, dolomite, and volcanic rocks. Coarse (conglomerate-sandstone) and variegated molasses are both of continental, lagoonal-continental, lacustrine, or less frequently near-shore marine origin.

Lower and upper molasses can be recognized in orogenic troughs.

The lower molasse is generally composed of bedded sandstones alternating with clayey sediments and limestones. Each rock type predominates interchangeably. The molasse was laid down at the beginning of the orogenic stage (Fig. 20).

The upper molasse is the result of the fast growth of the neighboring uplifts supplying enormous amounts of coarse debris to troughs.

The molasse also contains coal measures, which are highly characteristic of the troughs under discussion. These are made up of sandstones alternating with shales and coal seams and less frequently with limestones. The sediments accumulated in rivers, lakes, marshes, swamps, and lagoons, and occasionally on the sea floor. They are classified as paralic, that is, deposited on the sea coast and containing marine beds (for example, coal measures of the Donets Basin, just west of the Urals, and the Westphalia-Rhine Basin), and limnic, laid down under purely continental conditions in lakes, peat bogs, and swamps.

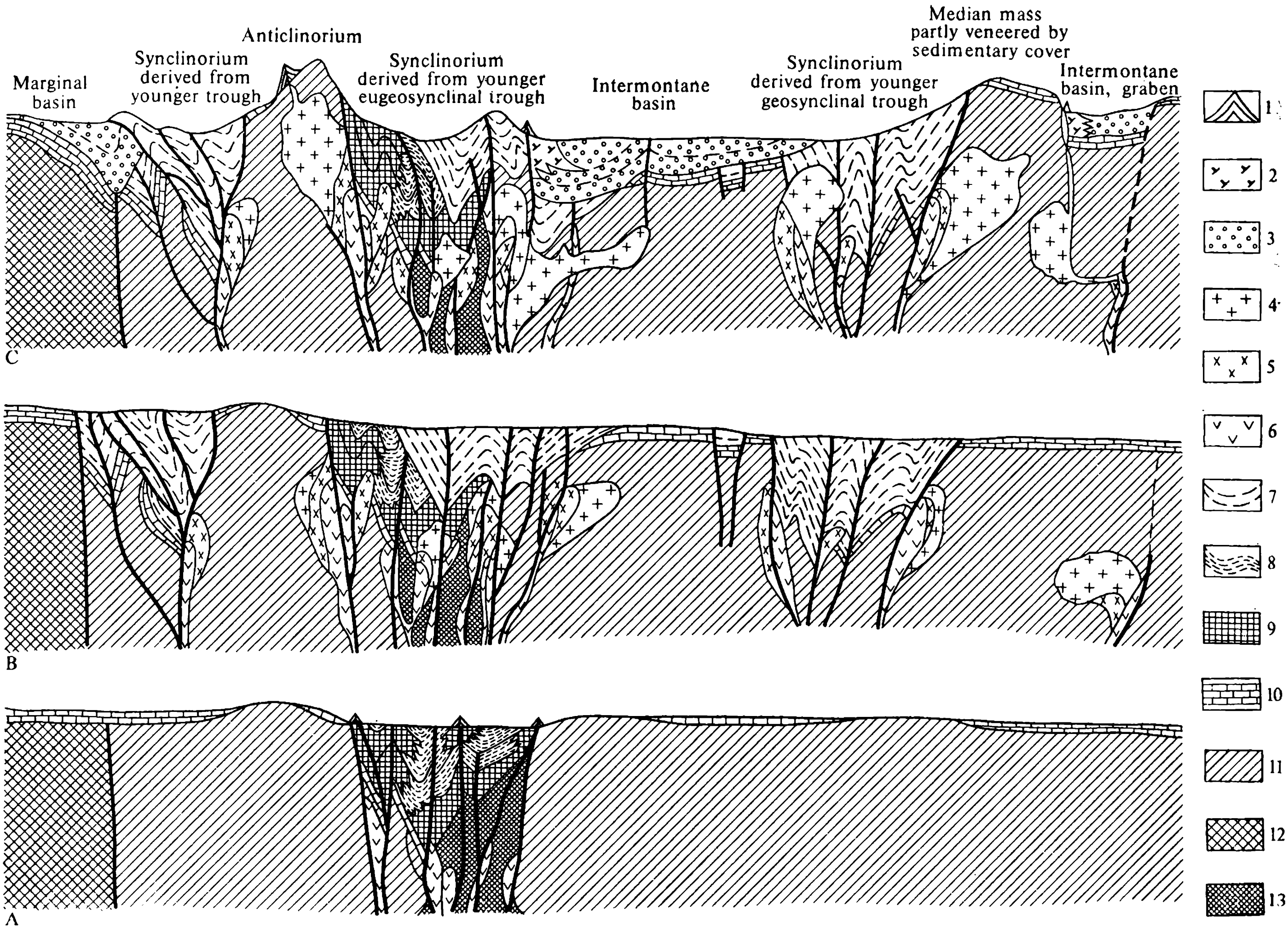
The molasse of intermontane basins and marginal orogenic troughs also contain salt-bearing formations. These consist of alternating clayey and sandy rocks with layers of dolomite, gypsum, and anhydrite. In many places gypsum and anhydrite occur as very thick lenses enclosed in molasse; these are intricately associated with beds of rock salt, up to many hundreds of meters thick, and occasionally of potash salt. A.L. Yanshin and R.G. Garetsky have found that such thick salt units accumulated rather rapidly over 2 000-3 000 years in a fairly deep lagoon.

Coal measures and salt-bearing formations are deposited in tectonically identical basins, but in different climates. In a wet (humid) climate, coal measures are laid down, and in a dry (arid) climate, salt-bearing formations. N.M. Strakhov illustrated this by the excellent example of the Uralian foredeep elongated along, and extending the length of, the Urals. In the north, in the Pechora River Basin, the Permian climate was wet, and the coal measures of the Vorkuta Basin accumulated.

To the south, in the Middle and Southern Urals, dry climate prevailed in Permian time, and the salt-bearing units of Solikamsk and the Southern Urals were laid down in the extension of the same foredeep.

An important role is also played by the clayey-coquina, or clayey-carbonate, formation consisting of an alternation of mainly shallow-water clays, sandstones, and limestones, including coquina.

The volcanogenic formations of molasse are highly specific. Some of them were erupted by volcanoes restricted to deep-seated faults many of which cut across the margins of intermontane basins. Hence volcanic rock complexes are


Marginal basin
Synclinorium derived from younger trough
Anticlinorium
Synclinorium derived from younger eugeosynclinal trough
Intermontane basin
Synclinorium derived from younger geosynclinal trough
Median mass partly veneered by sedimentary cover
Intermontane basin, graben
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located in many regions at the walls of these basins, but some of their members and layers extend toward their centres. The volcanogenic formations of orogenic troughs differ greatly in composition from basic through intermediate to acid rocks lying interchangeably. The formation that comprises all these rock types is classified as basalt-andesite-dacite. It is made up of lavas and related tuffs and breccias. Toward the deepest portion of the trough, the volcanic rocks thin out and are replaced by sedimentary rocks.

A specific liparite-dacite or porphyric formation is recognized in many areas of orogenic troughs, where acid lavas and tuffs (liparites and dacites) predominate. Clastic rocks, tuffs, and ignimbrites are always present in great amounts.

Higher-alkali volcanic formations are often common within the margins of troughs and adjoining median masses. The evidence for higher alkalinity is afforded by the presence of trachytic and trachybasaltic lavas and tuffs (trachybasalt-andesite formation) and in some areas even of nepheline-bearing rocks, which crystallize only if there is an excess of sodium in the melt.

To complete our review of the formations of orogenic troughs, we should note that within mountain areas sedimentation is scanty. Volcanogenic formations are the most common here; they make up volcanic plateaus, consist of lavas and tuffobreccias, and are found to be associated with big volcano cones.

DIFFERENCES IN AGES OF GEOSYNCLINAL AREAS AND IN FORMATIONS OF TROUGHS

Geosynclinal fold areas have very long histories. Hundreds of millions of years passed between the origin of fault systems and of the geosynclinal troughs subsiding along them and the cessation of all geosynclinal processes. Moreover, geosynclinal areas differ greatly in the age and duration of the basic stages in their evolution (Table 4).

In the Baikalian fold areas, the orogenic stage, which is indistinct in some

Fig. 20. Schematic presentation of the main stages in the evolution of a geosynclina area in the light of magmatic phenomena:

A — beginning of main stage (early phase);
B — end of main stage (mature phase);
C — orogenic, or final stage;
1 — volcano;
2 — volcanic series of molasse;
3 — molasse;
4 — secondary granitic magma chamber (products of metasomatism and partial melting);
5 — secondary granitic magma chamber (differentiation products);
6 — primary basic magma chamber;
7 — sedimentary sequence of mature phase and ate troughs;
8 — sedimentary sequence of early troughs;
9 — basic extrusive rocks in early phase;
10 — sedimentary cover of platform or median mass;
11 — foundation rock of geosynclinal area;
12 — basement of ancient platform;
13 — basaltic layer of earth's crust or rocks of mantle

Table 4

Typical Fold Areas of Different Ages (main stage is shown by hatching and orogenic stage

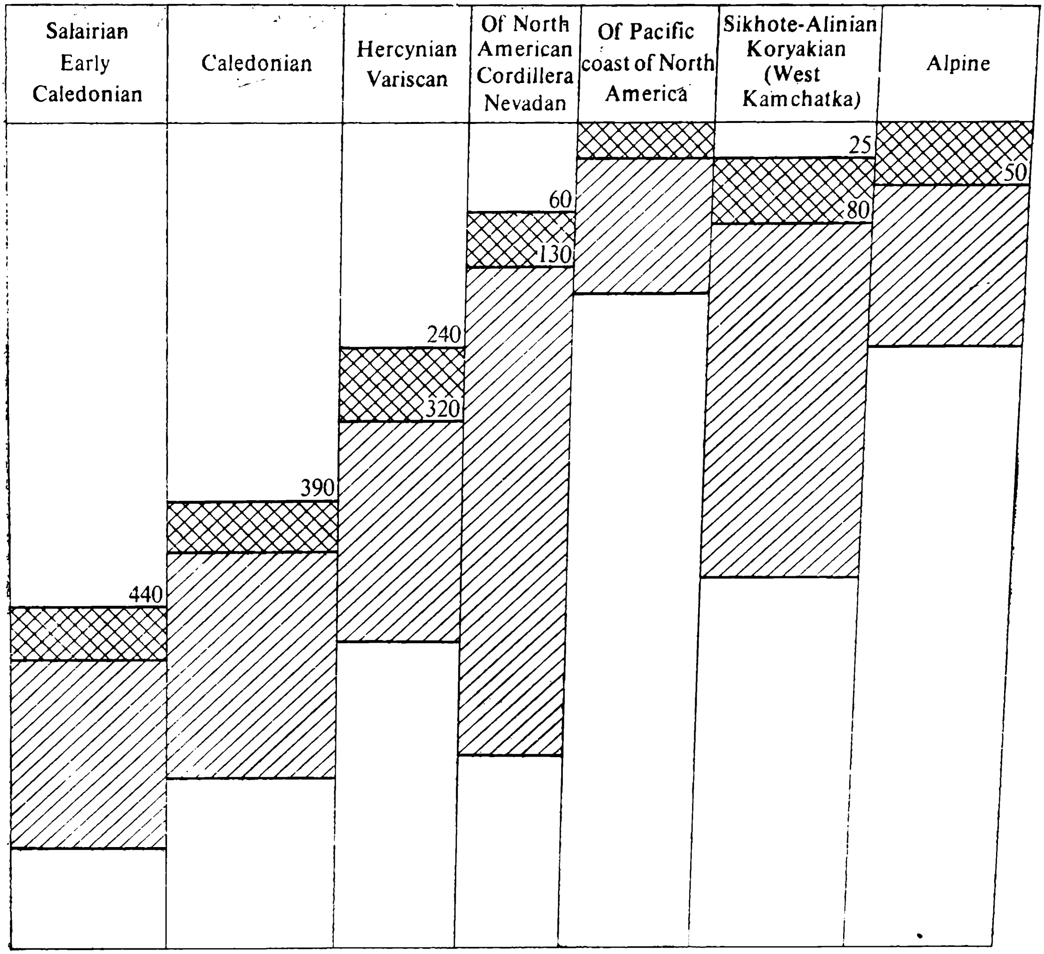
Era	Period	Karelian	Kibarian (Africa), Tuvian, and Early Baikalian	Baikalian, Katangian (Africa), and Cadomian (France)
Paleogene	Neogene			
	Oligocene Paleocene Eocene			
Mesozoic	Cretaceous			
	Jurassic Triassic			
Paleozoic	Permian Late Carboniferous Middle Devonian			
	Early Carboniferous Late Devonian Middle Devonian			
	Early Devonian Silurian Late Ordovician			
	Early and Middle Ordovician Late Cambrian			520
	Middle Cambrian Early Cambrian		900–11000	
Riphean	Vendian Late Riphean Middle Riphean Early Riphean			800
Proterozoic	Middle Proterozoic Early Proterozoic	1750 1850		
Archean	Archean			

regions, took place late in the Riphean, but occasionally continued into the beginning of the Cambrian.

Early and late Caledonides are recognized in the Caledonian fold areas. The main stage for the early Caledonides is assigned a Riphean-to-Cambrian age, and the orogenic stage spanned the end of the Cambrian and the Ordovician. In the areas of late Caledonides, or the Caledonides proper, the main stage stretched across the late Riphean, Cambrian, Ordovician, and the beginning of the Silurian, and the orogenic one lasted from late in the Silurian to the beginning, and in some places to the middle of Devonian time.

On all the continents, the Hercynian fold areas are characterized by the near coincidence of the time the main and orogenic stages occurred. The former began at the end of the Riphean, in the Cambrian, or in the Ordovician

by cross-hatching; figures designate ages of time boundaries in millions of years)



and continued through the Silurian and Devonian till the end of the Early Carboniferous. The latter took place during Middle and Late Carboniferous and Permian times and terminated at the outset of the Mesozoic, and sometimes early in the Triassic.

In the Mesozoic (Cimmerian) fold areas, the main stage extended from late in the Paleozoic (Carboniferous and Permian) through the Triassic to the Jurassic, and the orogenic stage from late in the Jurassic to early in the Cretaceous. In the other (Laramian) areas, the main stage was longer and continued to the end of the Cretaceous, whereas the orogenic stage ended at the beginning of the Paleogene.

The Alpine fold area is distinguished by the fact that the main stage of its geosynclinal cycle continued from the Mesozoic (Triassic or Jurassic) to the

end of the Paleogene, whereas the orogenic stage continued from the end of the Paleogene or the beginning of the Neogene to the end of the Neogene, including the Quaternary.

The age of the stages of geosynclinal cycles is the basis for making distinctions and correlations between them, though the age is not necessarily the same for different geosynclinal areas.

Various types of troughs (geosynclines) are recognized by the composition of their contained sedimentary and volcanogenic formations.

The most frequently used classification is that by G. Stille, according to which geosynclines proper, or eugeosynclines, and miogeosynclines are distinguished. The former are constantly characterized by diabase and basalt (spilite); the latter by thick limestone and dolomite.

Eugeosynclinal troughs are generally in the interior of geosynclinal areas, while miogeosynclinal ones are on their margins. An example of such an arrangement is the Urals fold area, where the system of interior Paleozoic troughs with abundant volcanism is in the eastern Urals, while the trough on the western side, along the East European platform, is filled with platform-type sedimentary series lacking volcanic products. A similar picture is seen in the Appalachian fold area of Paleozoic age, the Rockies, and many other areas.

As a rule, the sedimentary rocks filling miogeosynclinal troughs grade into those of the sedimentary cover of the neighboring platform and often cap median masses. Miogeosynclines are not deliniated by deep-seated faults; they are wide basins whose included rocks are folded, rather than narrow troughs filled with folded rocks. Hence perhaps they should not be referred to as true geosynclinal troughs, but, according to Stille, as a special type of troughs, with sediments similar to those on platforms, though by convention the common term miogeosynclines can be retained for them.

True geosynclinal troughs with little volcanic manifestations are sometimes also called miogeosynclines. But this is incorrect. There exist troughs with slight volcanism, but otherwise true eugeosynclinal, as in the Major Caucasus filled with thick sandy-clayey series. Also, miogeosynclines are also known with slight volcanism along some of the faults. Distinctions between them should not be made on the basis of formal criteria, but of the basic features. Even if weak volcanic activity occurs in a eugeosyncline, it is still a large, elongated, and long-living downwarp delineated by faults.

A miogeosyncline is a shallow downwarp filled mainly with platform-type, relatively thin piles of carbonate or clayey-sandy rocks.

The true geosynclines are often classified by the types of their included formations as volcanogenic, terrigenous, flysch, limestone, and so on. Such subdivision is sometimes convenient, but often plunges into a difficulty, particularly where a long-living geosynclinal trough was first filled with volcanic rocks, then clayey (terrigenous) rocks, and finally flysch. Here, the puzzling problem is to what category it should be assigned. In this case, we should formulate a more complex definition based on this series of rocks.

THE ROLE OF INTRUSIVE COMPLEXES IN THE GEOSYNCLINAL CYCLE

We shall now look at one of the most perplexing and important problems—the role of intrusive igneous rocks in the structure of geosynclinal fold areas and the circumstances under which they formed. As a rule, igneous rock masses are invariably present in geosynclinal fold areas. They vary widely and are of intricate shapes when emplaced. Many ores and other valuable minerals are found to be associated with these rocks; hence their exploration is of utmost importance.

Giant igneous rock masses are known to crystallize from magma at various depths within the earth's crust. In fold areas, they are not only numerous, but also extremely diverse in mineralogic and, hence, chemical composition, being composed of ultrabasic (dunite and peridotite), basic (gabbro), intermediate (diorite and quartz diorite), and acid (granitic) rocks. Intrusive bodies whose component rocks are related to one another in origin and age, but differ in composition constitute intrusive complexes.

Five principal complexes of igneous rocks are usually recognized in fold areas. The first comprises intrusions of ultrabasic rocks—peridotite, dunite, and others—very intimately associated in origin with mantle materials. Many scientists, such as A.V. Peive, A.L. Knipper, and M.S. Markov, have shown that most masses of these rocks were squeezed out from the mantle along faults while in a solid state. Although they are intrusions, they have nothing to do with the process of emplacement of intrusive rocks and are independent of other intrusive bodies derived from magma. Furthermore, having been intruded into the upper crust, peridotite, dunite, and other ultrabasic rocks are easily chemically altered by water and thus changed into rocks mainly made up of serpentine, a hydrous silicate. Along with such protrusions from the upper mantle, there also occur true intrusive bodies of peridotite, pyroxenite, and dunite which invaded sedimentary and metamorphic rocks along faults and are closely related in origin to gabbro and other basic rocks.

The second, true magmatic, complex corresponds in age to the early phases of the main stage of the geosynclinal cycle. It comprises basic intrusions (gabbro), in some regions associated with more acid rocks (diorite), and the corresponding volcanic rocks (diabase, spilite, basalt, and their tuffs).

The third complex pertains to the late (mature) phases; it is composed of andesite and intrusive diorite, granodiorite, and similar rocks.

The fourth complex is that of the orogenic stage and is characterized by granite intrusions, particularly by huge granite massifs. Other rocks of this complex (granodiorite and diorite) are present in some areas, but in subordinate amounts.

The fifth complex is composed of alkalic rocks with higher alkali (K_2O and Na_2O) content. As to the time of emplacement, however, this complex is closely associated with the two preceding ones, differing from these in the composition of the source magma and in that tectonically they are localized in median masses and margins of platforms.

In recent years, relationships and modes of formation of magmatic complexes and igneous rock formations occurring in geosynclinal areas have been very thoroughly investigated, particularly by Yu.A. Kuznetsov (1964).

As mentioned above, the earth's mantle is the source of magma for both volcanic and intrusive rocks to be emplaced. From the mantle, the material rises along deep-seated fault zones as a molten magma and partly as solid fragments of ultrabasic rocks carried out or squeezed out from the upper mantle. On its way upward from the mantle, the basic (basaltic or gabbroic) magma forms numerous chambers, that is, cavities filled with the magma or the materials replaced by it, near the base of the earth's crust. Being a viscous liquid, the magma is capable of moving from deep within the mantle, where it is under very high pressure, into zones of lower pressure. Systems of faults cutting across the crust are just such zones, and the magma invades them from below and then penetrates into the shattered zones between crustal blocks. On its way it slows down and gradually accumulates in deep-seated growing chambers. The blocks of the earth's crust are pushed aside during the formation of geosynclinal troughs, promoting this process.

In turn, deep-seated chambers are the source of magmatic melts which rise to the surface of the crust through faults and fissures and are erupted as enormous basaltic lava flows, tuffs, and other volcanic products. In geosynclinal troughs, eruptions take place beneath seas, with outpourings of spilitic lava flows associated with small intrusive bodies, such as dikes, sills, and laccoliths composed of gabbro.

But during very strong crustal movements along faults, fragments or a kind of wedges of solid ultrabasic rocks move upward from the upper mantle and are squeezed out on to the surface. This combination of rocks is typical of the ophiolite complex of an early phase in the development of a geosyncline.

Studies of many fold areas indicate that basaltic magma chambers occur along faults and are very large at the base of the earth's crust. Their magmatic melt exists for a very long time and undergoes differentiation. Olivine and pyroxenes, more refractory silicates rich in magnesium and iron, crystallize first with lowering temperature of the molten magma and are settled by gravity. During the further crystallization of the magma, gabbro and similar rocks rich in olivine, pyroxene, and plagioclase form in the lower portion of the cbamber. Feldsparfree (ultrabasic) rocks may also sometimes originate.

On the contrary, the magmatic melt of the higher portion of the chamber is enriched in less refractory components containing much SiO_2 and deficient in heavy iron-magnesium silicates. Its crystallization may lead to the formation of gabbro, gabbro-diorite, and diorite.

The magmatic melt filling the chamber and not fully crystallized may well be affected by crustal block movements and squeezed out along faults into the upper portions of the earth's crust. With its large volume, high temperature (over 1000 °C), and original volatiles (carbon dioxide and water), the melt is chemically very active. On its way upward, it can strongly act upon sedimentary, previously emplaced igneous, and metamorphic rocks and cause, under the influence of hot vapors and gases, considerable metasomatic changes of their mineralogic composition. The great heat flow from the magma may cause not only profound changes in the composition of the

enclosing rocks, but also their melting to form a granitic melt.This melt may then enter the chamber, with the resulting enrichment of the melt in SiO_2, that is, increase in magma acidity. In some cases, the digestion of sedimentary rocks by the melt also makes it enriched in SiO_2. In the other, the melt obtains additional lime (CaO) through assimilation of limestone, or alkalis (K_2O and Na_2O) at the expense of clayey rocks to produce more alkali-rich rocks.

In this complicated way, the chemical composition of magma is altered, and the melts more acid than the source basaltic or gabbroic melt fill large secondary chambers within a geosynclinal area in the higher portions of the earth's crust. These magma chambers also supply volcanoes with extrusive materials through deep-seated faults and the intricate system of outgrowing minor faults. These materials, however, are mainly composed of andesitic lavas, their tuffs and associated rocks: porphyrite, keratophyre, and others.

The magma of secondary chambers gives rise to intrusives of diorite, granodiorite, and similar rocks whose composition is that of porphyritic and andesitic lavas. Also, some of the emplaced bodies are even more acid, granitic in composition.

The andesitic volcanism and associated plutonism are known to occur in the mature phase of the development of a geosynclinal trough. Toward the end of this phase, granodiorite and granite predominate among intrusions. Moreover, on rising from below along faults, they cause upheaval of the overlying strata and at places even uprising of the earth's surface. Hence the growth of many geanticline uplifts simultaneously with marine sedimentation on their surface may be brought about by igneous intrusions.

As follows from above, the chemical composition of igneous rocks systematically grades from that of basaltic magma toward that of andesitic (intermediate) magma. The same is true of the mineralogic composition of intrusive bodies. On the whole, the complicated process of magmatic product changes during the main stage of the geosynclinal cycle is the result of both protracted magma differentiation in chambers and metasomatism effected by escapes from the basic magma, with the transformation of sedimentary and metamorphic rocks and their subsequent assimilation by magma.

When the magma digests the older sedimentaries and metamorphics, it does not necessarily become more acid. Some magma chambers assimilate basic volcanic rocks—basalt and tuff—or basic metamorphic rocks, with the resulting deficiency in SiO_2. On the other hand, hybride rocks may form when the acid magma absorbs basic igneous rocks or the gabbroic magma. Finally, as mentioned above, the acid magma may well dissolve such carbonate rocks as limestone and dolomite to become enriched in Ca and Mg and in alkali (Na).

Therefore, magmatism develops along the line of the increasing volume of the granitic magma in the main stage of the geosynclinal cycle, but sometimes the opposite occurs and the magma becomes more basic and hybrid rocks are thus emplaced.

Magmatism develops through a vast stretch of time. Suffice it to say that in most Paleozoic geosynclinal areas, the main stage, and the relevant magmatism, spanned the period from the Ordovician to the mid-point of the Carboniferous, that is, approximately 200 million years, and in the Alpine

fold area from the Jurassic to the beginning of the Neogene, that is, about 170 million years.

Most important in the orogenic stage is the granitic magma emplaced as bodies ranging from thin veins and stocks to large intrusions and huge batholiths. Contrary to the previous stage, the resulting granites contain more K than Na.

During the formative phase of granodioritic or andesitic magma chambers, further metasomatism and granitization of enclosing rocks appear to take place, with a great increase in the volume of the granitic magma. At the same time, some of the minor granitic magma chambers also grow rapidly. In the orogenic stage, very large granite bodies were emplaced in many fold areas. The increase in the volume of granitic magma chambers occurring at relatively shallow depths of approximately 2 to 4 kilometers was caused by active introduction of new magmatic material. The result was an upheaval of their roof to form mountain ranges.

In many Paleozoic fold areas, which became stabilized long ago and are now deeply eroded, granite massifs represent precisely the consolidated and now exposed chambers. These, often giant intrusions invariably extend along the corresponding fold area. They can be seen in the Urals, Tien Shan, and Altai, Mongolia, the Hercynian fold area of Western Europe, and in other regions. They are particularly long, up to thousands of kilometers, in the Rockies. In the Urals, the intrusions are smaller, from 50 to 100 kilometers long, but they form the strip that extends the length of the Urals (Figs. 21-23).

No such granite intrusions are found in the Caucasus and Alps. They have not yet been exposed, but appear to exist beneath the axes of mountain areas of the Major Caucasus and Alps and many other ranges. Indirect evidence for this hypothesis is afforded by outcrops of small granite bodies restricted to faults, which may be considered a kind of offshoots of major

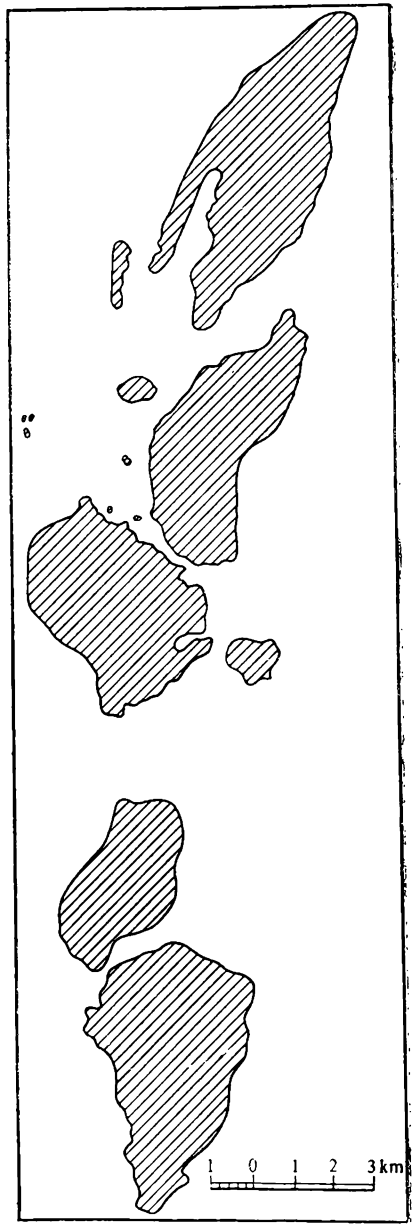


Fig. 21. A location map showing the outgrowths from a granitic batholith in the core of the Kochkar anticlinorium in the Middle Urals

granite chambers perhaps not fully consolidated in these regions.

Many scientists, as well as the writer of this book, believe that huge granitic magma chambers directly affect mountain-building during the orogenic stage in the development of the geosynclinal fold areas. The beginning of major orogenic uplifts in this final stage of the geosynclinal cycle is related to the increase in the volume of the granitic magma and the resulting enlargement of chambers.

A big granite body is often termed a batholith. According to geophysical evidence, its shape may resemble a giant round or long loaf or a roll. It has a feeder entering from below or from its side, through which batches of granitic magma were added to the chamber. This chamber may have been covered by the thick consolidated portion of the magmatic body. Hence the entering material enlarged the chamber and raised, like a giant hydraulic press, its cover and the roof to produce an archlike structure.

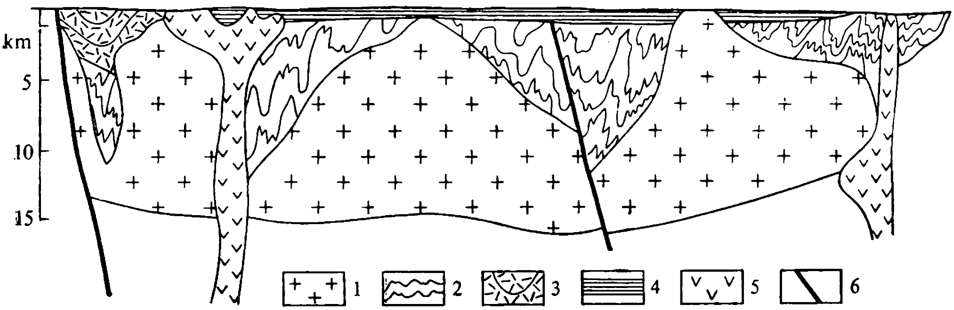


Fig. 22. **A supposed shape of the granitic batholiths in the Middle Urals as shown in the cross-section based on geophysical evidence:**

1 — Late Paleozoic granite;
2 — upper Proterozoic metamorphic rocks;
3 — Silurian and Devonian;
4 — Lower Carboniferous;
5 — ultrabasic or basic intrusion;
6 — fault

When the arch rised and a mountain area grew, more or less considerable zones of transverse and longitudinal fractures may have cut through the rocks involved. The magma ran through these zones on to the surface, and either volcanic materials were thrown into the air one time or great stratovolcanoes were constructed over a long period.

In the course of the evolution of a geosynclinal area, which may have continued scores or a few hundred-million years, a wide spectrum originated of magmatic bodies and volcanic extrusions differing in composition.

The basic source magma forming in the mantle and entering the earth's crust within a geosynclinal area gives rise to major and minor chambers and changes in its own chemical composition. It becomes more acid and is ultimately transformed into a granitic melt containing more K. This melt is produced in enormous volumes while intruding dislocated piles of sedimentary, igneous, and metamorphic rocks or partly replacing and melting them. In these processes, magma plays an active role and often upheaves

Fig. 23. A location map showing large granitic batholiths in the North American Cordillera:

I — batholith of Sierra Nevada;
II — Aidaho batholith;
III — batholith of Canadian coast

the overlying rock column, which causes the above-mentioned mountain building (Fig. 24).

Cooling then leads to complex and undoubtedly slow crystallization of the magma of granite batholiths and of other chambers. The magma solidifies through several phases during which the most volatile components of the melt, rich in water and a number of active agents, are expelled into the enclosing rocks where these hot vapors and gases cause complex changes in the mineralogic composition of sedimentary and igneous rocks. The process

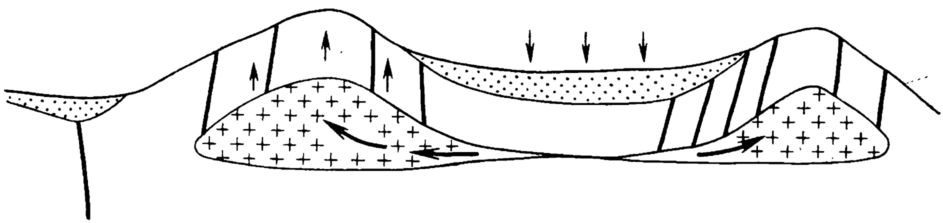


Fig. 24. Schematic presentation of the supposed relationship between the formation of the basins and uplifts of the orogenic stage and that of granite bodies (batholiths)

is often accompanied by rearrangement and concentration of certain minerals. Hence the contents of minerals similar in chemical composition and of commercial value may increase, that is, mineral deposits may form.

GEOSYNCLINAL AREAS: PROLIFEROUS SOURCES OF VALUABLE MINERALS

Geosynclinal fold areas are a natural storehouse of great mineral wealth. That is why knowledge of their structure and history is not only of theoretical interest for understanding processes in the earth's crust, but also of extremely great practical importance. In other words, this knowledge is indispensable for the right explanation of the circumstances under which mineral deposits formed and for successful searching and prospecting for them.

Various metal ores are of paramount importance. All the richest deposits of copper, lead, zinc, silver, tin, gold, manganese, molybdenum, tungsten, arsenic, antimony, mercury, nickel, and cobalt, many deposits of iron, aluminum, rare metals, and uranium, and deposits of many non-metallic minerals (chromite, asbestos, fluorite, and others) were discovered in geosynclinal fold areas. Coal deposits are enclosed in sedimentary rocks of intermontane basins and foredeeps of geosynclinal areas.

The largest coal basins in the world, with numerous high-quality coal seams, are restricted to orogenic basins. These are the Kuznetsk and Donets Basins, USSR; Upper Silesia, Poland and Czechoslovakia; Saar and Westphalia-Rhine, FRG; Belgian Basin, Bristol and other coal basins of England; Asturias Basin, Spain; the great Pennsylvanian Basin, USA; and many others.

Many oil and gas fields were discovered in foredeeps and intermontane basins, though the most prolific of them are enclosed in supracrustal rocks of platforms.

The most valuable minerals found in fold areas are associated in origin with either volcanism or various igneous rock intrusions. Less important are minerals found in sedimentary rocks and some of the mineral materials formed by disintegration and weathering of igneous and sedimentary rocks.

Deposits of many minerals, most of which are directly or indirectly related to volcanism, were discovered in volcanic and sedimentary rocks that fill geosynclinal and orogenic troughs, and in the vicinity. Some of them are the outcome of initial volcanism on the bottom of a geosynclinal trough early in its evolution, the others originated later and are associated with andesitic volcanism of the mature phase, and still others are the result of orogenic volcanism of the final stage.

Two basic types of mineral deposits may be distinguished. One includes beds deposited on the bottom of a basin and enriched in iron, aluminum, and manganese oxides. The other, more complex in origin, comprises deposits of ores containing sulfides of many non-ferrous and rare metals.

Deposits of the former type are enclosed in volcanic and sedimentary rocks where lavas and tuffs alternate with sandstones, siliceous rocks, jaspers, and in some regions limestones and other rocks. Beds of siliceous-hematitic or iron-manganese rocks enriched to some extent in oxides of iron or manganese also generally occur. Less frequently individual beds with higher contents of various ore minerals are associated with them. When these components reach sufficient concentrations, the beds become ores. These are mainly iron ores consisting of iron oxides (hydrohematite, hematite, and magnetite), aluminum ores (bauxite), and manganese ores. Beds of iron and manganese ores generally alternate with volcanic and sedimentary rocks. Many deposits of iron and manganese of this type of ores are known in all parts of the world, especially those enclosed in geosynclinal series of Precambrian to Lower Paleozoic age. More scarce are bauxite deposits occurring, as a rule, in the shape of isolated beds.

The second type is represented by sulfide ore deposits which occur as layers of tuff or other rocks enriched in pyrite, to some extent chalcopyrite, and other sulfides. Layers containing commercial amounts of copper are referred to as copper ores (these are sometimes very rich), or lead-zinc ores (galena PbS and sphalerite ZnS) may predominate. Sulfide ores in volcanic-sedimentary sequences precipitated from water (hydrothermal) solutions carrying sulfur compounds, immediately after the deposition of a volcanic-sedimentary unit or at nearly the same time. Many deposits contain much silver, gold, and other metals in addition to copper, load, and zinc. Barite ($BaSO_4$) deposits of this type are also known.

Geosynclinal areas are also characterized by a great many sulfide deposits of copper, lead, and zinc surrounded by volcanic rocks. These are the zinc-lead deposits of the Rudny Altai (Leninogorsk, Zyryanovsk, and others) and Kazakhstan (Atazu), chalcopyrite deposits of the Urals, and rich copper deposits in Turkey (Madena) and Spain (Rio Tinto).

The structure and origin of sulfide deposits are difficult to decipher, because along with stratiform deposits in sedimentary-volcanic strata, sulfides may

often concentrate in adjacent voids and crevices clearly cutting across the surrounding sedimentary and igneous rocks and thus produce ore veins and irregular bodies. They are definitely younger than the enclosing rocks and are often quite rich in ores.

In the not-too-distant past these ores were related to the emplacement of acid intrusions. Hot fluids associated with the intrusions were considered to play the main role in the formation of ore bodies. Much importance was not attached to volcanism. In recent years, however, V.I. Smirnov, G.S. Dzotsenidze, V.N. Kotlyar*, and others have found that volcanic processes are of the utmost importance in the generation of ores, especially sulfide ones of copper, lead, silver, gold, and other metals.

This inference opens new possibilities for the discovery of ores in piles of volcanic rocks and makes it possible to search and prospect for ore mineral resources along new lines.

The above investigations have proved that volcanic processes not only govern the generation of stratiform sulfide deposits, often with rather lean ores, but also the accompanying circulation of vapors and hot fluids. These redistribute ore minerals, dissolve and transport sulfides from the original beds along systems of faults and fissures, and form new veins and cross-cutting bodies which may well contain high-grade ores.

Igneous intrusions invading geosynclinal sedimentary and volcanic rocks also exert great and differential influence on the commercial concentration of metals and many non-metallic minerals. Granite bodies are responsible for the widest spectrum of valuable minerals and the most intricate processes of their generation. However, ultrabasic, basic, and intermediate intrusions also govern their respective mineralization.

Deposits of iron (magnetite), titanium, (ilmenite), copper, and nickel ores may be associated with basic intrusions, while those of chrysotile-asbestos and chromite and some of the titanium deposits with ultrabasic dunite and pyroxenite. Ultrabasic rocks are sources of platinum and nickel. These metals, however, are so finely scattered that only erosion and weathering may bring about the natural enrichment of a rock in nickel compounds or grains of native platinum.

Large deposits of the various ores of economic value may be related to intermediate intrusive bodies, massifs of diorite, quartz diorite, and similar granodiorite. They are most frequently confined to the contact zone between the intrusion and the enclosing rocks, the latter being affected not only by the high temperature of the intrusion, but also, and in the main, by the fluids that are saturated with silica, alumina, magnesium and iron oxides, and alkalis (K_2O and Na_2O) and actively cause chemical changes in these enclosing rocks. Metasomatism occurs, and the larger the amounts of chemically active agents in the fluids, the greater the effect. Garnet, pyroxene, hornblende, magnetite, and other minerals form at the contact zone. Garnet-pyroxene rocks derived from rocks affected by intrusions were termed skarns. They may often enclose economically valuable magnetite. Also, skarns may contain deposits of the rare metals (tungsten and molybdenum repre-

* In 1972 these scientists were awarded the Lenin Prize for the substantiation of the role of volcanic processes in ore formation.

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sented by sheelite and molybdenite), copper (chalcopyrite and pyrite), and lead-zinc. The mineralogic composition of a skarn is extremely diverse, and the contact zone is the widest where an intrusive invades limestone or dolomite. In this case, many unique calcium and magnesium minerals appear in the contact zone. These are interesting for the mineralogist and are occasionally of practical value.

Granite bodies are responsible for many mineral concentrations and deposits. As shown earlier, their solidification is a very complex and protracted process. Two phases are distinguished: first, emplacement of a granitic melt, and, second, its slow crystallization and consolidation.

The granitic melt, which is enclosed in sedimentary, other igneous, and/or metamorphic rocks, looks as if it was in a giant boiler containing various molten and mixed constituents. These include the basic magma supplied from deep within the mantle and then undergone a long succession of transformations following differentiation and assimilation of enclosing rocks, and constituents of the surrounding sedimentary (sandstone, shale, and limestone) and igneous (older lava flows, tuffs, plutons, and others) rocks. In a granitic melt at some 1 000°C and a very high pressure, the physical and chemical conditions of a silicate melt prevail, approaching to some extent those of a blast furnace, but differing greatly because the natural processes are so enormous in extent. Indeed, the volume of the melt can reach scores or even hundreds of cubic kilometers.

The magmatic melt is essentially the silicate material that contains all the chemical elements forming minerals of the sedimentary, intrusive, igneous, and metamorphic rocks that gave rise to magma. It contains both relatively involatile (Si, Al, Ca, Mg, Fe, and Mn, minor amounts of Cu, Zn, Pb, and Au, and even lesser amounts of other elements) and highly volatile components (O, H, S, CO_2, SO_3, and other sulfur compounds), and haloids (Cl, F, B, and P).

Hot vapors originate deep inside the melt and then penetrate through it into the enclosing shell. They usually contain water vapor, carbon dioxide, and haloids, are greatly heated, and are highly energized chemically. These vapors cause metasomatic alteration in the surrounding rocks and are known to be capable of melting, under certain conditions, metamorphic rocks with the resulting increase in the total volume of the granitic melt.

The behavior of the melt is governed by geochemical laws under which various constituent chemical elements react with each other depending on the properties of their ions. Hence the elements are grouped according to their "affinities".

We do not know exactly how long such a granitic melt can exist. It depends, of course, on its rate of cooling, depth of occurrence, and size. Perhaps large and giant granite plutons with the huge mass of melt can exist in a molten state, gradually cooling for hundreds of thousands or even millions of years.

On releasing its heat, that is, on cooling, the melt begins to crystallize, first its surficial portions and then the deeper ones. Its outermost zones soon begin to be cut by fractures entered by batches of the melt which quickly crystallizes and forms veins corresponding in composition to the melt at depth. This melt sometimes starts to move; it breaks through and shatters the surrounding crystalline shell, invades the enclosing rocks, rises highly

and produces large completely isolated bodies. In other instances, a host of minor intrusions are emplaced. Because of magma differentiation, these bodies may vary widely in composition. Series of contemporary small intrusions are known of gabbro, diorite and various granites.

During the slow consolidation and crystallization, the most volatile and most easily fusible components of the magmatic melt survive in the residual melt to the very end; thus this melt is saturated with water and volatiles such as chlorine, fluorine, boron, and carbon dioxide. At the close of granite mass crystallization, this melt, which is rich in volatiles and hence very mobile, is squeezed as irregularly shaped bodies into the roof of the granite massif and generates peculiar pegmatite dikes which are valuable for their giant crystals of mica, feldspar, and many rare minerals.

Along with this, at the beginning of magma crystallization, the melt expells distillation products, mainly superheated steam. The water content of both the basic and acid molten magma is high. The higher the pressure, the more the amount of water dissolved in the melt.

According to N.I. Khitarov, the magmatic melt may contain up to 3.4 percent water by weight at 1 000°C and 2 000 atmospheres and 2.4 percent water at 1 000 atmospheres. Therefore, with such a pressure drop, one cubic kilometer of melt may release several scores of millions of tons of water vapor which can dissolve, at high temperatures, much silicates and other components of the melt. Volatile vaporous water solutions, or fluids, transfer the substances dissolved in them from the magmatic melt into the contact zone between the melt and surrounding rocks and, through fissures, into the latter.

The interaction of the fluid and the enclosing rocks leads to skarn formation at the contact. Along with skarns, hot emanations composed of steam saturated with highly volatile magma components form greisens. These rocks, deposited by hot vapors, consist of quartz and white mica (muscovite), with some tourmaline, topaz, fluorite, and albite and occur in the shape of stratiform bodies and veins. They occasionally make up systems of veinlets above generally small granite intrusions (other than batholiths), and also in the upper parts of these intrusive granites or granite-porphyries. Greisens are related only to the SiO_2-richest intrusions of granite (alaskite) and rather infrequently contain many ore minerals. The most valuable deposits found in greisens are those of tin (cassiterite SnO_2), tungsten, molybdenum, beryllium, lithium, and other metals.

The occurrence of ore veins and greisens in a large granite massif intruded during the orogenic stage and the cross-sectional structure of the massif itself is clearly exemplified by the metalliferous Akchatau granite massif in Central Kazakhstan (Fig. 25).

Hot emanations and solutions penetrate farther through the system of fissures from the magma chamber into the surrounding rocks. The superheated steam, saturated with magma components, above all SiO_2 and volatiles, cools gradually. On cooling, its resolving power decreases and various minerals precipitate from it filling fissures and thus forming veins. Thus a system of hydrothermal veins originates whose materials are deposited by magma-derived hydrothermal solutions. The veins are mainly composed of quartz, more seldom barite or carbonates (calcite, dolomite, siderite), and contain more

or less large amounts of other minerals whose components were carried out by hot solutions from the magma and precipitated together with quartz. Hydrothermal veins are often strongly mineralized, that is, their metal contents are economically valuable.

High temperature hydrothermal quartz veins with tungsten and molybdenum minerals and minable gold are the most common. Veins containing mercury (cinnabar) and antimony (antimonite) minerals originate at lower temperatures. Hydrothermal veins and other bodies often consist of the sulfide minerals of barium (barite), copper, lead, and zinc and are mined at a profit.

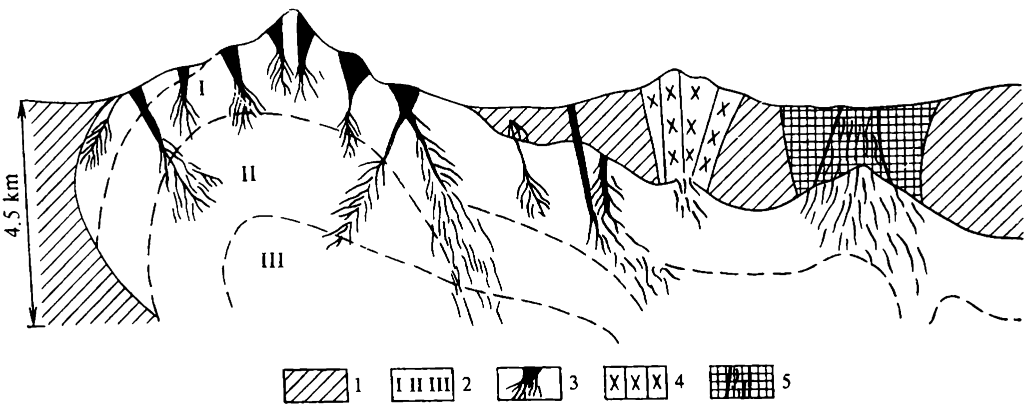


Fig. 25. Generalized presentation of structure of the Akchatau granite massif, Kazakhstan, and location of its contained ore veins and greisens. (Simplified after G.N. Shcherba, G.M. Laumulin, and N.P. Senchillo, 1972):

I, *II*, and *III* — zones of successive crystallization of massif from surface downward;
1 — surrounding sedimentary and volcanic rocks of Paleozoic age;
2 — granite;
3 — ore veins and greisen;
4 — vent facies;
5 — high-concentration stockwork mineralization zone in roof of massif

Thus, during the slow processes of formation and then crystallization of the magmatic melt and all the spectrum of the accompanying phenomena, complex rearrangement takes place of the elements disseminated in the melt irrespective of whether they come from deep within the mantle or are the result of metasomatism and partial melting of sedimentary rocks.

Some of the elements are left in the igneous rock under crystallization, others concentrate at the zone of contact with the enclosing rocks, still others combine with the most mobile and volatile components and leave the mass under crystallization together with hot fluids to fill veins of various composition.

To summarize, we observe a very interesting geochemical phenomenon: certain elements finely disseminated in the earth's crust and contained in negligible amounts in the magmatic melt itself, strikingly concentrate following the crystallization of magma and the escape of volatile components from it. This is precisely the process occurring in greisens, skarns, pegmatite dikes, and hydrothermal ore veins.

TWO PRINCIPAL TYPES OF GEOSYNCLINAL AREAS AND THEIR ROLE IN THE BUILD-UP OF THE GRANITIC-METAMORPHIC LAYER OF THE EARTH'S CRUST

Geosynclinal processes are apparently accompanied by folding, violent volcanism, various intrusions, and metasomatism and metamorphism of sedimentary rocks. These operate not only in the geosynclinal troughs proper, but also extend far beyond their limits into the neighboring median masses and geanticlinal uplifts. These phenomena are related to the deep-seated fault zones that are channelways for the magma with its hot emanations to rise from below. Moreover, large granite bodies originate after the emplacement and crystallization of huge granite batholiths in the orogenic stage. All this results in considerable transformation of the earth's crust in the entire geosynclinal area. Thus, sedimentary and volcanic rocks experience recrystallization and compaction and are severely intruded by igneous rocks.

The general compaction of material of a geosynclinal area is an expression of formation of the granitic-metamorphic layer of the earth's crust, which is thus the result of the geosynclinal process and accompanying phenomena. Two principal types of geosynclinal belts are clearly recognized, depending on their role in the origin of the granitic-metamorphic layer.

The first type includes geosynclinal belts whose trough systems were initiated in the oceanic crust, that is, in the basaltic layer of the crust covered by a thin veneer of sedimentary and volcanic rocks. Early in their history, systems of troughs delineated by faults, and uplifts existed on the ocean floor. These were expressed at the surface as submarine ridges and island chains separated by ocean deeps and narrow trenches.

The second type covers geosynclinal areas whose trough systems began to develop in the continental crust. Here, deep but narrow submerged depressions originated, as did extensive and more shallow basins at the site of median masses, with intervening lines of islands and growing mountain ranges. In these areas, fault systems broke the earth's crust into blocks which may then have been widely pushed aside. As a result, parts of the basaltic layer, or even blocks of the upper mantle's ultrabasic rocks may have been forced through faults to the bottom of some troughs.

Therefore, in the evolution of both the types of geosynclinal areas, mantle-derived materials were intruded in the early stages basically similar in different troughs. Initial diabase volcanism occurred and similar basic and ultrabasic rocks were intruded. Then sedimentary and volcanic series accumulated in the troughs and underwent folding. They were invaded first by basic rocks and second by intermediate rocks (diorite and then granodiorite). The early-stage basic (basaltic) volcanism was followed by the prevalence of intermediate (andesitic) volcanism of the mature phase (andesitic phase, according to A.V. Peive).

However, these processes operated along somewhat specific lines for each type of geosynclinal areas. In those initiated in the oceanic crust, sediments accumulated for a very long time and were folded and metamorphosed to gradually build up the granitic-metamorphic layer of the earth's crust. In the other type of geosynclines the granitic-metamorphic layer already existed. Its sections, blocks, and shattered masses were involved in the geosynclinal process and were metamorphosed, replaced, and melted once more. Under these conditions, the crustal material was transformed much faster, which thickened the earlier continental crust, whereas the geosynclinal cycle was shorter.

This distinction is understandable and can be explained by the fact that in the first type of geosynclines there was no material available initially to build up the continental crust, while in the second type of geosynclines the granitized material was already present and involved in the events.

In all types of geosynclinal areas, the thickest granitic-metamorphic layer was formed by repeated geosynclinal processes which involved in metamorphism and granitization segments and blocks of the earlier granitic-metamorphic layer.

A striking distinction can thus be drawn between the histories of the two types of geosynclines, though they are generally similar in stages and phases of their evolution. The distinction will be shown below as exemplified by particular geosynclinal areas in the various fold belts.

The systems of geosynclinal troughs in both types of areas are related to deep-seated fault zones cutting through the earth's crust into the mantle. The information on the depth of deep-seated faulting is supplied by the igneous rocks derived from the magma of the asthenosphere lying at depths some 50 to 200 kilometers. Therefore, the systems of geosynclinal troughs and faults that control them are conduits for this magma, as if they were giant crustal furrows that open the way for the interior material to come to the earth's surface. The geosynclinal process thus merely seals up these furrows—a kind of giant-scale welding. Moreover, this process appears to result in a radical transformation of the earth's crust. When it is protracted and, especially, repeated, a granitic-metamorphic layer, the chief constituent of the continental crust, is produced.

The entire granitic-metamorphic layer was not created at once. It was first initiated in isolated areas, beneath ridges and islands that grew on the sea floor along faults. Strips and segments of the floor underlain by the oceanic crust still existed between them, and on the whole the crust was of the transitional type. Gradually, the granitic-metamorphic layer built up and became more and more extensive.

V

STRUCTURE AND HISTORY OF THE BASEMENT OF ANCIENT PLATFORMS

MAJOR STRUCTURAL UNITS

Now that we have outlined the tectonics of the continents and the role the ancient platforms play in their structure, we shall more thoroughly explore the history and structure of ancient platforms.

The basement has so far been more or less thoroughly explored only for several of the platforms, mainly within shields. The Baltic and Ukrainian shields of the East European platform have been studied more than the Canadian shield of the North American platform and the Aldan and Anabar shields of the Siberian platform. The basement structure of the shields of the ancient platforms in Africa, India, and Australia is known, but it has been little explored in South America and within other platforms.

The data now at hand suggest that the basement of all platforms has common features. The basement complexes will no doubt attract more and more attention in the near future, because its metamorphics enclose deposits of valuable minerals, such as high-quality iron ores, gold, non-ferrous metals, uranium, micas, and many others.

The basement of the platforms has a long history in which the accumulation of sedimentary and volcanic materials, folding, and metamorphism played a prominent part. We can see in some regions that the various igneous rock complexes were emplaced repeatedly.

On the best-studied platforms, the basement was found to consist of two types of structural units: large blocks or massifs made up of metamorphosed igneous and sedimentary rocks of Archean age and massifs of younger fold systems in-between. The latter occur in strips between ancient massifs and are composed of metamorphic rocks involved in fold structures trending along the strips cut by faults, and intruded by basic, ultrabasic, and acid

igneous rocks. Granitic rocks occasionally build up huge massifs. All these sedimentary and igneous rocks are for the most part of early Proterozoic, less frequently of middle Proterozoic age.

THE STRUCTURE OF ARCHEAN MASSIFS

In detailed studies of metamorphic rocks that make up Archean massifs, two complexes differing in age and structure have been recognized. The oldest is probably early Archean in age, the younger, late Archean. The former consists mostly of amphibole and biotite-amphibole gneisses and amphibolites occasionally intercalated with members of ferruginous rocks rich in magnetite and hematite, and with metamorphosed diabases, that is, volcanic outpourings. These rocks are at least 3 800 million years old. Ancient complexes crop out in a great many places. They have originated from the sedimentary and volcanic rocks that accumulated on the floor of a sea or an ocean and were later transformed into gneisses and other metamorphic rocks. Some of the series are made up of basic lavas and tuffs, the others of an alternation of sedimentary and volcanic rocks, peculiar ferruginous and ferruginous-siliceous muds metamorphosed to jaspilite, also a product of underwater volcanism. This type of rock is well known from the Dnieper massif of the Ukraine (Konsk-Verkhovtsev series), the Aldan shield within the Siberian platform (Iengr, Chara, and other series), the Canadian shield (Keewatin series), Australia (Kalgoorlie shield), the South African platform (Sebakwayan and Bulawayan series), and many other shields.

In some places the oldest basic series consists of pyroxene-plagioclase schist and gneiss, that is, granulite, associated with small gabbroic and ultrabasic bodies. No amphibole gneiss occurs here. These rocks, including the amphibole gneiss, were probably derived from basic volcanics and tuffs alternating with sedimentary series. The difference is that the pyroxene-plagioclase rocks were metamorphosed at great depths (granulite facies), while the amphibole gneiss and amphibolite formed at shallower depths (amphibolite facies). Some scientists believe that granulite—pyroxene-plagioclase gneiss—and the accompanying basic igneous rocks are protrusions or sections of the basaltic layer that is found by geophysical methods.

The second complex of rocks that builds up the Archean massifs comprises more or less thick gneisses which may in some areas be subdivided into many series of somewhat different composition. For example, the Aldan complex, which makes up the Aldan shield of the Siberian platform, and the Belomorian (White Sea) complex, which constitutes the Belomorian Massif of the Baltic shield of the East European platform, each are up to 8 000-10 000 meters thick. They are composed mostly of amphibole, two-mica, and biotite gneisses intercalated with members of amphibolites and marble. Units are also present containing various aluminiferous gneisses and schists with sillimanite, cordierite, and staurolite, minerals rich in Al_2O_3. These complexes are generally distinguished by a distinct bedding succession and form persistent series.

Similar complexes are also known from other ancient platforms and appear to have been marine sediments alternating with volcanic members that were later deeply metamorphosed. Those well-sorted sandy-clayey sediments were supplied from the neighboring land and deposited in the slowly sagging depressions of the sea floor.

The above complexes are late Archean in age (2 600 to 3 000 million years old), which is, however, difficult to determine because of subsequent metamorphism.

Many scientists believe that these gneiss complexes originated in peculiar extensive and little-dissected troughs. After sedimentation the rocks were folded and deeply metamorphosed (amphibolite facies). They are intruded by contemporaneous, predominantly basic rocks (gabbro, gabbro-labradorite, and anorthosite), and also by ultrabasic bodies (peridotite). Then many of the rocks of the given complexes experienced very intricate deformation, which was due to later granitization and migmatization. In some regions they were found to make up large domal structures attributed, as is commonly thought, to their plastic or even mobile state during migmatization and granitization rather deep inside the earth's crust. Structures of this kind are called granite-gneiss domes. Their origin is still largely obscure, but they were distinguished on many shields such as in the Ukraine (within the Dnieper Massif), on the Aldan shield of the Siberian platform, in South Africa, and on the Guiana shield.

Many Archean rock masses later underwent extensive superimposed metamorphism and granitization. The result is the vast development of migmatites and granites which disturb the structure of the more ancient rocks or simply substitute for many of them. In many places, only relics or even xenoliths (small blocks and chunks) of the original Archean rocks remain. According to radiometric dating, the superimposed processes within the Archean massifs took place late in the lower Proterozoic or in the middle Proterozoic, that is, at the same time as granitization and metamorphism of the neighboring lower and middle Proterozoic fold belts, and in the late Proterozoic. In some places these phenomena were accompanied by intrusion of large and complex younger bodies of various granites, gabbro-labradorites, and other rocks building up a kind of stratified massifs (Korosten' intrusive complex of the Ukraine and others).

Such Archean massifs, which experienced later granitization and metamorphism, are known from many platforms. On the East European platform, it is the large Kirovograd-Zhitomir Massif, of the Ukraine, and the Near-Azov Massif. Contrary to the others, this massif displays granite intrusions containing much alkalis, as proved by the presence of nepheline. Such an alkalic granite is called mariupolite. Large Archean gneiss massifs, metamorphosed in the Proterozoic, are also known from the Canadian shield (Massif in the Churchill River drainage basin), North African platform, southern Hindustan platform, and many other shields of ancient platforms.

The Archean massifs and their parts later granitized and metamorphosed form extensive sections, or nuclei, of the ancient platforms. These are the southwestern corner of the East European platform, namely, the basement of the Voronezh anteclise and part of the Ukraine; the large Belomorian Massif in the central and northwestern East European platform; the eastern

half of the Siberian platform; the southern and southeastern Canadian shield (the Massif of Lake Superior) and the second Slave Massif in northwestern Canada; the very extensive part of the North African platform; the South African platform, which occupies Central Africa and possibly makes up the basement beneath the Sahara Desert; probably the Australian platform; and many other regions of ancient platforms. Therefore, the Archean massifs apparently constitute over 70-75 percent of the total area of ancient platforms.

PROTEROZOIC FOLD AREAS

As mentioned above, the Archean massifs, which make up the basement of ancient platforms, are separated and rimmed by strips of folded Proterozoic rocks forming relatively narrow fold systems and sometimes occurring in broader areas.

Such areas and systems have not been found on all the platforms. They are, for example, unknown on the Siberian platform. This, however, may be due to inadequate knowledge of the basement under the sedimentary cover.

On the Baltic shield, the basement of the East European platform is divided into four Proterozoic fold areas: the Kola, Karelia, Svecofennian and Dalslandien. Moreover, a system of fold strips was delineated in the basement of the Russian sediment-covered platform by geophysical methods.

The fold areas of the Baltic shield have been studied best. The Kola and Karelia areas are separated by the Belomorian Massif of Archean age. The Kola area consists of two early Proterozoic strips of folded and metamorphosed sediments extending the length of the Kola Peninsula from the northwest to the southeast. These are separated by the Kola Massif of Archean age and bordered by the Murmansk Massif on the north.

Each of the strips is composed of rocks grouped into the Karelian complex. These are garnet-biotite and amphibole gneisses, and amphibolite; also alumina-rich schist occurs (Kayv formation). All these rocks are invaded by basites (gabbroic rocks) and granites. Originally, they were volcanic and sedimentary series accumulated on the sea floor where violent submarine outpourings took place. These series are crumpled into very steep folds and fill synclinoria, narrow and long troughs.

The age of the lower complex is estimated at between 1 800 and 2 300 million years, and that of intruding bodies 1 750 and 1 800 million years.

The fold structures of the Karelian system have much in common and are of equal age. They do not, however, form continuous strips, but a number of more or less broad and short stretches. Structurally, Karelian rocks are involved in fold structures many of which are synclinoria invariably deliniated by faults. The fold structures group in four to five zones extending from the north-west to the south-east across Karelia and the neighboring part of Finland into Sweden in the north. They are made up of metamorphosed volcanic and sedimentary rocks of the lower Karelian complex in some places with intercalations of units containing iron ore beds, and are intruded by gabbroic rocks and granites. The lower complex of the Karelian is of the same age as the similar units of the Kola Peninsula. The upper complex

is here less clearly delineated and composed of sandstones and conglomerates intercalated with diabases of the Sariolite series. It is much thinner (up to 1 500 m) than the similar units on the Kola Peninsula, and is less extensive.

The composition of volcanic-sedimentary series and the presence of the two complexes differing in composition and occurrence are features highly characteristic of geosynclinal fold areas widespread in young fold belts.

Here we only note that the lower Proterozoic and middle Proterozoic fold series of the Kola Peninsula and Karelia can also be referred to as geosynclinal fold areas. The occurrence of the two complexes is of special interest. The lower sedimentary and volcanic complex accumulated in both cases in relatively narrow geosynclinal troughs. The now observable synclinoria filled with these sediments are remnants of previously broader troughs.

Consequently, the Kola and Karelia fold areas are examples of the most ancient true geosynclinal areas. They are characterized by volcanic outpourings and granitic intrusions.

Systems of throughs buried under the sedimentary cover of the East European platform, more concretely, the eastern and central parts of the Russian sediment-covered platform, have been found by geophysical and drilling techniques. They appear to be the southeastern extension of the system of fold troughs of the Kola and Karelia areas. These systems form a giant ramified arc. The rocks that fill these troughs are early Karelian in age. Those belonging to the Yatulian of Karelia are also apparently present.

To the south, within the Voronezh basement protrusion and the Ukrainian shield, a number of early Proterozoic fold troughs run in a north-south direction. They contain the well-known iron ore deposits (Kursk Magnetic Anomaly and Krivoy Rog) and are separated by Archean massifs (Fig. 26).

The Svecofennian fold area differs considerably in composition and structure. It occupies much of Sweden and Finland and extends, according to geophysical evidence, under the sedimentary cover beneath the Baltic Sea into Latvia and Estonia. It is separated from the Karelia fold area by a deep-seated fault zone and in one region by the Karelia-Finland Massif of Archean age.

The Svecofennian fold area consists of several tightly bending strips composed of differently metamorphosed rocks. These stretch from Sweden across the Gulf of Bothnia into Finland.

The strips are made up predominantly of fine-grained quartzo-feldspathic gneisses called leptites, which were derived from acid volcanic products, that is, lavas or tuffs of the type of liparite, dacite, and others, and partially from clays. There occur intervals of basic volcanics and occasional layers of marbles and iron ores.

Huge granite massifs, the oval Central Finland Massif 250 km along the long axis being the largest of them, are located between the strips of the deeply metamorphosed folded series, in the loops of the arcs formed by them. There are two generations of granite: early and late. The former is about 1 880 million years old, the latter 1 730-1 800 million years old. As to the composition and structure of sedimentary and volcanic complexes, the Svekofennian area resembles typical geosynclines to a lesser extent. The orogenic (upper) complex is here only slightly developed, is present

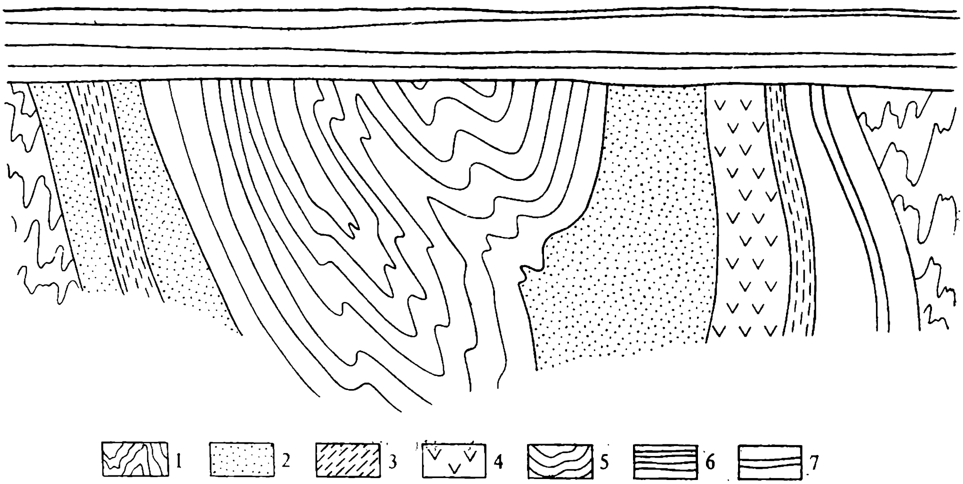


Fig. 26. The occurrence of the Kursk series of Proterozoic age in a geosyncline. The Chernyansk iron ore deposit, the Novo-Oskol region, the Voronezh crystalline massif of the East European platform. (Simplified from A.K. Romanshchak):

1 — Archean gneiss: Kursk iron ore series of lower Proterozoic;
2 — metamorphic schists;
3 — lower beds of ferruginous quartzite;
4 — amphibolite and schist;
5 — upper beds of ferruginous quartzite;
6 and *7* — sedimentary cover of platform: Jurassic, Cretaceous, and Quaternary sediments

only at places, and consists of sandstone and conglomerate. But the area is very similar in age to the Karelia and Kola fold areas and may also be referred to as early Proterozoic.

In Kiruna County, northern Sweden, and in West Sweden and South Norway, the lower Proterozoic and middle Proterozoic fold areas were granitized and metamorphosed in middle to early late Proterozoic times. These processes were radiometrically dated as active between 1 725 and 1 540 million years ago. They were accompanied by large granite intrusions and at places acid lava extrusions, as exemplified by the Kiruna porphyry containing large deposits of high-quality iron ores. Late granitization, accompanied by acid porphyritic lava outpourings, involved the Gotland Massif of South Sweden approximately at the same time (1 750 to 1 500 million years ago). Later metamorphism and granitization occurred in South-West Sweden, west of Lake Vänern, and in Telemark County, southern Norway. Here, folded Dalsland and Telemark rocks apparently of early Proterozoic age were metamorphosed about 1 000 million years ago (the middle of late Proterozoic time) and partially melted by granite of the same age (Bochus granite in Sweden). Metamorphism and granitization of part of the basement took place in Byelorussia 1 400 to 1 300 million years ago.

On the North American platform, the lower to middle Proterozoic rock complex is called the Huronian and consists of series filling narrow, but deep depressions of the type of geosynclinal troughs folded and metamorphosed during the Hudsonian folding 1 850 to 1 750 million years ago (during mid-Proterozoic time). They run from Lake Superior northeastward and

then abruptly turn to the north-west across the Labrador Peninsula. The second belt of folded Huronian rocks extends along the east shore of Great Slave Lake northeastward. The third belt is near Great Bear Lake in North-West Canada. The vast area between these belts is occupied by an Archean massif that again underwent granitization and metamorphism during the Hudsonian folding.

In the western North African platform, the Birrimian fold area is of early to middle Proterozoic age. It stretches from the coast of the Gulf of Guinea through Togo, Upper Volta, Ghana, and Guinea to Sierra Leone northward to be then buried under the sedimentary cover. Its northward continuation may be within the Reguibate shield (West Sahara). The age of the granite intruding the Birrimian system is 1 650-1 850 million years. The Birrimian metamorphic complex is similar in composition to the Karelian, and the Tarkwaien sandstone involved in superimposed basins may be classified as an orogenic complex.

The lower and middle Proterozoic fold areas are fairly common on the Hindustan platform. Three fold systems of different ages are usually recognized in southern India: the Dharwar, Eastern Ghats, and Satpura.

The Dharwar area is made up of several broad and narrow synclinoria running from north to south within the state of Mysore. They are filled with terrigenous and basic volcanic rocks intercalated with iron ore layers transformed to schist and gneiss. The rocks are 2 200 to 2 450 million years old, that is, early Proterozoic in age. The strips of these rocks are separated by what is called the Peninsula gneiss of Archean age, which builds up small median masses. The rocks were granitized and metamorphosed 2 300 million years ago. This fold system is apparently older than the Karelian but is still early Proterozoic.

The radiometric age of folding of the Eastern Ghats area in southeastern India, obtained for intrusions, is between 1 585 and 1 150 million years ago.

The third, Satpura system to the north is even younger; its folding dates at 1 000-900 million years ago. These systems, however, are more likely parts of a single fold area separated by a gneiss massif of Archean age, and they are similar to the Carelides in age. Two geosynclinal fold complexes, main and orogenic, are distinguished in each of the two parts. Numerous dates on granites and other rocks are available for the Eastern Ghats part, indicating that its folding and final intrusions are not younger than 1 500 million years. The Satpura is made up of fold structures consisting of thick series of schist, amphibolite, and marble intruded by granite and pegmatite dikes with valuable muscovite deposits and many rare minerals. According to dates on their component minerals, these dikes are of Proterozoic age, that is, they were emplaced 900-980 million years ago.

At places the area is underlain by platform-type sediments of the Vindhyan and Cuddapah series, which are at least 1 400-1 500 million years old. Consequently, the rocks that underlie them are older than the late Proterozoic. The pegmatite dikes apparently postdate the folding of the area.

On the China platform, the Uthai-Khuto system belongs to the lower and middle Proterozoic areas. It is similar in age to the Karelian system and has both geosynclinal complexes, the main (Uthai) and the orogenic (Khuto).

Distinct fold systems of early or middle Proterozoic age have not been found on the Siberian platform, nor in Australia and South America.

All in all, there are nine lower or middle Proterozoic fold areas. They are the earliest among fold areas derived from true geosynclinal systems and hence are of great interest. They differ only slightly from each other and from common younger geosynclinal areas.

THE PROTOSEDIMENTARY COVER OF ANCIENT PLATFORMS

On many ancient platforms, areas are present where the crystalline basement is still overlain by sandstones, quartzites, clayey rocks, dolomites, and volcanic outpourings resembling in the mode of occurrence a sedimentary cover, but considerably differing from the sedimentary cover of a platform. Being generally early Proterozoic in age, these series are older than the true extensive sedimentary cover. In some places they are metamorphosed to amphibolite facies, and in this sence are closer to the basement than to its cover. True, such profound metamorphism does not manifest itself everywhere, but only in some places such as in the Kodaro-Udokan region of the Siberian platform. These series may be folded and invaded by various intrusions, including granitic ones. Several scientists (A.M. Leytes, M.S. Markov, E.V. Pavlovsky, and others) call them a protosedimentary cover.*

The series of the protosedimentary cover accumulated under two types of structural environment. They occur either in narrow, occasionally complicated grabens, or in more or less vast basins looking like fairly gentle, at places faulted, synclines. Both types are intruded by vast sheets of varying composition, that is, the intrusions are considerably differentiated ranging from gabbro to diorite and granite.

The most typical examples of the protosedimentary cover were found in the following regions.

In the Kodaro-Udokan region (Chara River), Aldan shield, Siberian platform, the protosedimentary cover occurs both in grabens and in large basins. It is intruded by a complicated granite body. The rocks vary in age between 2 500 and 1 900 million years ago (early Proterozoic).

On the Baltic shield, East European platform, the protosedimentary cover is formed by the Yatulian complex. It occurs in a number of synclines separated by uplifts (anticlines) some of which are slightly disturbed by minor folding. The complex is not strongly metamorphosed and not intruded, except for diabase and gabbro dikes. The total thickness of the Yatulian quartzite, clayey rocks, and dolomite is 600 to 1 000 meters, their age ranging from 1 800 to 1 600 million years ago (middle Proterozoic).

The final stage of their deposition is marked by the emplacement of very large coarse-crystalline granite massifs called rapakivi (Wiborg Massif and others, between 1 650 and 1 610 million years old). On the Kola Peninsula,

* Protosedimentary cover precedes the true sedimentary cover of a platform.

the protosedimentary cover is composed of sandstone and chlorite-sericite schist which are similar to the Yatulian, but thicker (6 000 to 8 000 meters).

On the Canadian shield, within the Massif of Lake Superior of Archean age, there is a very complex series of Huronian (lower to middle Proterozoic) quartzite and schist up to 2 000 meters thick. It is intruded by the differentiated Sudbury Massif (gabbro, diorite, and granite) with the largest copper and nickel deposits in Canada.

Sandstones of the protosedimentary cover are known in Guiana, within the ancient South American platform (Roraima). The protosedimentary rocks underlie much of the South African platform in Transvaal. Here, they are up to 13 000 meters thick, are made up of several series of sandstone, conglomerate, lava, and dolomite, and enclose large gold deposits of South Africa. These rocks are invaded by the complex Bushveld intrusion consisting of gabbro, alkalic rocks, and granite with various metal deposits, including uranium.

OUTLINE HISTORY OF THE BASEMENT OF ANCIENT PLATFORMS

According to the above information, the basement of ancient platforms is composed of Archean massifs and lower and middle Proterozoic fold areas.

The Archean massifs, which make up the most ancient blocks, consist of two principal units: masses or strips of the oldest metamorphic rocks (gneisses of basic composition) known from ancient platforms and granite gneisses that build up the complicated, occasionally very thick and extensively granitized complexes. Accordingly, three major stages can be distinguished in the history of the deformed and metamorphosed basement complex of ancient platforms. In the first stage, early Archean volcanic and sedimentary rocks accumulated; in the second stage, Archean massifs of granite gneisses originated; and in the third stage, Proterozoic fold areas developed. These last are elongated and strongly resemble geosynclines. The first two stages continued throughout the Archean, and the third stage took place during early to middle Proterozoic time. In this stage, a protosedimentary cover was also laid down on a number of massifs.

The oldest stage spans the time interval between 3 600 million years, in some places even 3 800 million years, and 3 300 million years. The series of this age generally makes up small patches, or stretches of the strips, and parts of folds within limited areas. It is composed of metamorphosed volcanics interbedded with sedimentaries deposited on the floor of the sea that covered the surface of the earth's crust consisting of only the basaltic layer. Not all of the crust was covered by ocean at that time. Some of its areas rose above sea level and were being worn down. The most ancient crust of basic composition was thin and hence easily broken up or cracked. Magma penetrated through these cracks with the resulting violent volcanic activity. Lavas, tuffs, breccias, and other volcanic products accumulated over vast tracts of both the sea floor and land. On land, the volcanic rocks underwent

erosion and destruction; they were transported by water streams and redeposited on the sea floor as beds of sea-bottom sediments similar in composition to volcanic products.

We can suggest that in the early Archean the earth's crust was geographycally rather homogeneous. That is why the most ancient Archean rock complexes that make up the basement of ancient platforms on different continents have very much in common. Examples are the above Keewatin series of Canada, Kola series of the Baltic shield, Konsk-Berkhovtsev series of the Ukraine, Kalgoorlie series of Australia, Kayana of Guiana in South America, Sebakway and Bulaway of South Africa, and Iengr and Chara series of Siberia.

All are but remnants of volcanic series that once covered the most ancient basaltic crust of the earth. These series together with crustal rocks, such as gabbro, anorthosite, and basalt, were incorporated in the composition of the basement as a result of subsequent formation of the granitic-metamorphic basement of ancient platforms, with the accompanying phenomena of breakup and block movement.

The second stage started from the middle of the Archean, that is, from about 2 300-3 000 million years ago. At this time parts of the earth's crust originated; they consisted mainly of rocks of granite-gneiss composition, and thus the most ancient parts of the granitic-metamorphic layer formed. This process was apparently related to the differentiation of the earth's surface into highly uplifted sections undergoing erosion and those downwarped and subsiding below sea level and receiving great thicknesses of sediment. These downwarped sections were not yet true geosynclinal troughs, which began to form later, but extensive elongated basins at sites of future continents. Sedimentary and volcanic sequences up to 6-8 kilometers or more in thickness accumulated in them. E.V. Pavlovsky called these downwarps protogeosynclines, that is, forerunners of geosynclines.

The protogeosynclines were filled with the materials supplied from the land after the wearing-down of volcanic rocks. At that time, basalts and associated rocks were weathered in an atmosphere free, or almost free, from oxygen, consisting of nitrogen and carbon dioxide. Hence no strong oxidation of destruction products occurred and there was no true chemical weathering. As a result, the basins were filled with clayey material somewhat richer in alumina and with chemically laid carbonate sediments. Owing to compaction and metamorphism, they were converted into gneisses that often contain cordierite and sillimanite. This is precisely N.V. Frolova's explanation of the origin of alumina-rich sillimanite and cordierite gneisses with interbeds of marble and quartzite, which were found on the Siberian platform. She has proved that they are the result of erosion and redeposition of products of volcanic rock destruction.

Downwarps filled with the Belomorian series of late Archean age and other penecontemporaneous sediments perhaps belong to the long-existing structures of similar intense sedimentation that formed in the middle of the Archean within the East European platform. They appear to have been shallow, and their contained sediments were folded, metamorphosed, and granitized at the end of this cycle and thus transformed into folded Belomorian gneisses and schists.

Specific gneiss and gneissoid granite domes are highly characteristic of the Archean in the areas of gneisses. This structural type is recognized by many explorers as a feature of the ancient Precambrian tectonics. Within the East European platform, we can see them in the Dnieper Massif in the Ukraine, and in the Belomorian Massif. They have not yet been found in other massifs on this platform, because they are buried under the sedimentary cover and hence have been little studied. Fortunately, these domes are well known from roughly contemporaneous series of the Aldan shield within the Siberian platform, of South Africa, of Guiana, and of many other regions on other ancient platforms.

The domes are usually oval-shaped and more seldom have winding or amoeba-like outlines, and are 50 to 100 kilometers in diameter. The constituent gneisses are strongly folded on the margins of the dome and form an arch in its center, where they may often be replaced by a granitic massif.

With the thick series accumulating in the downwarp, and with the thin underlying primary oceanic crust, the lower layers of the sedimentary column were greatly influenced by a strong heat flow from the mantle. The upper parts of the sedimentary sequence served as a blanket and helped accumulate heat and melt the lower layers. Subsequently, these plastic, mobile masses were forced upward by non-uniform loading or tectonic forces into the overlying rocks to produce more or less large gneiss and gneissoid granite domes.

The oldest early Archean gneisses and younger late Archean gneisses were gradually deformed on the margins of the domes and between them, and were folded. A granitic magma then crystallized in the domes and their cores. The result was rigid granite-gneiss platform-type massifs of Archean age.

These processes ceased late in the Archean, about 2 600-2 500 million years ago, that is, during the Belomorian folding within the East European platform.

From the very beginning of the Proterozoic, systems of true geosynclinal troughs delineated by faults started to form. Some of them dissected the surficial granitic-metamorphic layer of the earth's crust, and the basaltic substratum protruded into them; the others, such as the troughs of the Svecofennian area of the Baltic shield, were localized entirely in the granitic-metamorphic basement.

The early Proterozoic troughs resemble typical geosynclinal ones. They are characterized by a mature main geosynclinal complex and a more poorly developed orogenic complex. Considerable differences between the areas can be outlined. Within many of these areas strong granitization took place, which involved not only the systems of geosynclinal troughs proper, but also the intervening massifs. Some of the Archean massifs were fully granitized. For example, within the Öland (Gothian) granite massif of the Baltic shield, South Sweden, the Öland complexes have almost fully disappeared; they have been replaced by younger Gothian granite, with the result that their unaltered remnants can be seen only in few places. These processes were accompanied by outpourings of Öland porphyry metamorphosed at the contacts with granite. Late-stage granitization was noticed in the Ukraine, in the Stanovoy Range on the Siberian platform, and in other places.

In addition, in the early and middle Proterozoic, the most ancient protosedimentary cover started to accumulate on the Archean massifs between the systems of geosynclinal troughs. The earliest units of the cover are sediments filling grabenlike troughs. Examples are systems of troughs of the southern Siberian platform and the Timiskaming basin on the Canadian shield. A protosedimentary cover was then deposited on some massifs (Udokan series of Siberia, Yatulian of Karelia, and Transvaalian of South Africa) intruded by intricate igneous rock complexes and metamorphosed.

At the same time, sections of the basement of ancient platforms were further granitized and metamorphosed to give rise to rigid massifs with the generation of a thick granitic-metamorphic layer and its transformation to a craton.

The first of these stages in the history of the basement of ancient platforms is considered prehistoric relative to the basement of a platform. It relates to the earliest time in the early Archean life of the earth's crust, when no continental crust existed, but a primary melanocratic basaltic crust approaching the modern oceanic one. It may have contained several different isolated sections, but no continental sections were present with a granite-gneiss layer, nor was the earth's crust divided into geosynclines and platforms.

The second stage marks late Archean accumulation of thick sedimentary series in extensive troughs, or protogeosynclines, their metamorphism, and granite magma formation. In the end, the earliest massifs emerged having a granitic-metamorphic layer and hence being continental in structure.

The third stage took place in the Proterozoic and is characterized by initiation of first geosynclinal-type troughs, their development, folding and granitization, and generation of early Proterozoic fold areas. Along with this, the oldest units of the protosedimentary cover were laid down in graben-like troughs or on separate massifs.

THE BASEMENT OF ANCIENT PLATFORMS: MINERAL RESOURCES

Many large mineral deposits were discovered in the basement and the protosedimentary cover of the ancient platforms. Some are associated with accumulation of volcanic and sedimentary rocks on the bottom of ancient Archean seas and in Proterozoic basins, others with volcanism, still others with igneous intrusions, and the rest with metamorphism.

Iron ores are undoubtedly the most valuable materials found in the basement. These make up large valuable deposits, syngenetic with volcanics and laid down during the Archean, discovered in early Proterozoic geosynclinal troughs of the Kursk Magnetic Anomaly and Krivoy Rog region on the East European platform. High-quality iron deposits are known from the North American, Hindustan, North African, Australian, and other platforms.

Copper-nickel deposits (Pechenga, Moncha, and others on the Baltic shield) are also of major importance. Titanium ores are related to basic

rocks. High quality gold and uranium deposits are enclosed in conglomerate-sandstone series of the protosedimentary cover on some platforms. The most famous are those enclosed in the Witwatersrand series, South Africa, which are the largest source of gold in the world and a major source of uranium ore. Gold-rich conglomerate is known from the Huronian series, Canada (near Lake Huron). Similar conglomerates occur in Brazil and West Africa.

Manganese deposits are also important; they are made up of manganese-rich minerals enclosed in metamorphic complexes (Singhbhum district on Hindustan platform).

To summarize, the basement of ancient platforms, buried over vast territories under the sedimentary cover, contains deposits of many highly valuable minerals. They will no doubt be explored further in searching for new mineral deposits occurring at depths.

VI

HISTORY OF FOLD BELTS AND FORMATION OF THE BASEMENT OF YOUNG PLATFORMS

GENERATION OF THE RIPHEAN BASEMENT OF MAJOR AND MINOR BELTS

After its consolidation, the granitic-metamorphic basement of ancient platforms became separated by vast areas of would-be fold belts. So far very little is known about their early history. The data are available mainly on the late Proterozoic (Riphean era) and later times. Some parts of the fold belts supply information on somewhat earlier, early and middle Proterozoic events, but almost nothing is known about the Archean stages.

Thus the pre-Riphean basins, whose bottoms resembled those of the present-day oceans, appear to have existed in the Ural-Mongolia, Atlantic, and Mediterranean belts. The granite-gneiss layer of the continent-type crust was probably present there solely as local massifs.

A.V. Peive (1969) was the first to pay attention to the major role played by the ocean-type crust, that is, by the protrusions of the basaltic layer in fold areas early in their geosynclinal history. Now his conception has been widely recognized.

In all probability, the basaltic layer, which made up the base of the ocean-type crust and was covered by a thin veneer of oceanic sediment, formed early in the evolution of all the seven major and minor belts. However, little information is available on this early oceanic crust beneath the belts.

This series of basic volcanic rocks (diabases) associated with gabbro and ultrabasic bodies were found in many places beneath geosynclinal sedimentary and volcanic rocks. They appear to correspond to the oldest basaltic layer of the earth's crust. These rock types locally protruded through the great zones of faults and thrust faults to the surface in the Urals, Kazakhstan, and Altai-Sayan fold area, on Newfoundland, and in many other regions of fold belts. The protrusions of the basaltic layer indicate that at the outset, the ocean-type crust occupied much of the belts.

It was only since the Riphean that conditions were created for thick geosyncline-type sedimentary and volcanic series to accumulate in some of the troughs. The evidence for this is the wide distribution and great thicknesses of the upper Proterozoic rock complexes which in many regions consist of extrusive-terrigenous series, 6 000 to 10 000 meters thick, typical of geosynclinal troughs and containing spilite-diabase, volcanic-siliceous, jasper, and other formations. The ophiolite association with ultrabasic bodies is also very important.

Thus the geosynclinal cycle, with the deposition of terrigenous-volcanic complexes within all the belts, began with initiation of troughs in the ocean-type crust. Then marine sediments accumulated in them. Judging from the distribution of the upper Proterozoic (Riphean) sedimentary-volcanic complexes, they were laid down over enormous expanses of the belts. Apart from the Riphean geosynclinal complexes, sediments are also known that were deposited on the flat, slightly sagging sea floor.

The geosynclinal areas were probably represented by systems of lines of islands related to faults, with volcanoes sitting on them, and deep intervening troughs. Volcanic and sedimentary series accumulated in these troughs. The faults were the result of tension or lateral movements in the earth's crust that caused slipping along these faults. Narrow depressions, occasionally looking exactly like yawning gaps, formed between them; they just served as troughs where volcanic products were deposited alternating with marine sediments. Then the sedimentary and volcanic series were deformed in these troughs. They were intruded by igneous rocks and, following subsidence, metamorphosed. Conditions originated at depth for the formation of granitic magma chambers which partly solidified and crystallized *in situ*. Some of them, however, built up granite bodies intrusive into the overlying rocks or the flanks of the troughs.

As a result of repeated folding and metamorphism during the Riphean, the sedimentary and volcanic rocks were transformed into thick deformed and metamorphosed complexes invaded by numerous intrusions and at places granitized.

Two major foldings occurred in the Riphean. The first took place in the middle of the Riphean, that is, from about 1 300 to 1 000 million years ago, and has no generally accepted name. It is called the Kibarian for the Intra-African belt, Minasian for the Brazilian belt, and the Isedonian for the Ural-Mongolia belt. The second, Baikalian folding pertained to the end of the Riphean and lasted from 700 to 500 million years ago.

In the middle of the Riphean era, folded and metamorphosed sedimentary and volcanic sequences formed in the Intra-African and Brazilian fold belts. Within the former, these are the following extensive strips and massifs restricted to its margins: Kibara, Ankole, Burundi, Karagwe, Irumi, and others. Within the latter, similar extensive massifs originated during the Espinasian (1 200 million years ago) and Minasian (1 000 million years ago) foldings.

Then geosynclinal processes went on in the narrower basins between these massifs. Here, sediments filled the basins, and processes of deformation, metamorphism, and intrusion operated. At the very end of the Riphean, during the Baikalian folding, the geosynclinal cycle came to an end, and

the entire area of the Intra-African and Brazilian belts became the basement of a young platform.

In the Paleozoic, sedimentary and volcanic rocks began to accumulate on this basement. This means that the geosynclinal cycle came to a close in minor belts, as if they welded together the edges of the neighboring ancient platforms. As a result, as early as the beginning of the Paleozoic, the continents of Africa and South America became huge continuous blocks of platforms, unlike Asia and Europe.

At probably just that time, the giant southern continent of Gondwana emerged and joined together the platforms of South America, Africa, India, Australia, and Antarctica. Subsequently, it gradually disintegrated into parts separated by the Indian and Atlantic basins.

In major belts, the Kibarian folding in the middle of the Riphean and the folding at the end of the Riphean (after the Baikalian folding) also resulted in the formation of major and minor masses and vast platforms. Many of them have survived inside the fold belts and now occur as median and marginal masses. No continuous platforms, however, originated within the fold belts and the major fold belts went on their geosynclinal cycle in the regions where the basement was still absent and a relict oceanic crust was present. Also, geosynclinal processes were renewed in many areas of the basement produced by the middle or end of the Riphean. As a result, the basement was broken up and involved in new systems of geosynclinal troughs which existed till the middle or the end of the Paleozoic or even Mesozoic.

On the margins of the belts, the extensive fold areas adjoining the ancient platforms have the Baikalian basement. Thus the vast Baikalian area follows the eastern margin of the Ural-Mongolia belt running along the boundary with the Siberian platform from the Taimyr Peninsula through the Yenisei Ridge to Lake Baikal. The Timan-Pechora area stretches along the northeastern edge of the East European platform. The Mediterranean belt is also fringed on the south, along the edge of the North African platform, by the strip of the Baikalian fold area of Morocco and Algeria (Atlas Mountains) which then enters Tunisia where it is buried under the sedimentary cover. On the north, near the edge of the East European platform, the belt is bordered by the strip of the Baikalides of the Karakumy Desert, the Northern Caucasus and the Crimean plains, and the Lower Danube Lowland (the Miziisky sediment-covered platform). Then it appears to continue westward through Central Europe. In the Circum-Pacific belt, there are two areas of the Baikalian folding: that of Adelaide, near the edge of the Australian platform, and that of South-East China.

The central parts of the belts contain numerous relatively large massifs whose basement consolidated in middle Riphean time or during the Baikalian folding. Thus the vast Kokchetav-Ulutau, Muyun-Kuma, and Kirghizia massifs have been found in Central Kazakhstan, Ural-Mongolia belt. Similar massifs probably underlie the sedimentary cover in the Lake Balkhash area and in the central part of the West Siberian sediment-covered platform. The Khingan-Bureya Massif is the biggest; it occupies a huge area on the eastern margin of the belt. This massif may be partly made up of a fragment of an ancient platform.

In the Atlantic belt, the ancient massifs of the Scotland Highlands, the massif east of the Appalachians, on the US Atlantic coast, and other massifs can be considered similar to the above.

In the Mediterranean belt, the largest pre-Baikalian (middle Riphean) massif occupies the central part of Iran, and Afghanistan. Several massifs are located in the Caucasus and Turkey (Transcaucasian, Georgian, and that in central Asia Minor), on the Aegean Islands, the Balkan Peninsula (Rhodope and Macedonian massifs), and in the Carpathians. A huge massif is buried under the sedimentary cover of the Hungarian Lowland. The Baikalian massifs are found in Czechoslovakia (Bohemian), in the Rhine (those of Schwarzwald and Vosges), in France (Central and Armorican massifs in Brittany), on the Iberian Peninsula (Iberian Massif), and in Italy (Calabrian Massif, and other massifs). Also, the vast Indochina Massif (perhaps a small ancient platform) makes up the southern Indochina Peninsula.

In the Circum-Pacific belt such massifs are represented by the basement of Honshū Island, Japan; the Omolon and Chukot massifs, USSR, and others.

To summarize, a thick granitic-metamorphic basement was produced at the end of the Riphean over vast expanses of major fold belts and over entire minor ones.

The development of the geosynclinal areas throughout the upper Proterozoic (about 1 000 million years), with the accumulation of enormous thicknesses of volcanic and sedimentary rocks intruded by igneous rocks and repeatedly folded and metamorphosed, has generated extensive metamorphic and folded rock complexes. They occupy limited areas only in the Circum-Pacific belt and are absent from the eastern Mediterranean belt, namely, Indonesia.

FORMATION OF THE PALEOZOIC BASEMENT OF THE URAL-MONGOLIA, ATLANTIC, AND ARCTIC BELTS

The minor fold belts had ceased to be the active sections of the earth's crust by the beginning of the Paleozoic. The major fold belts have a story of their own. Geosynclinal processes within them operated not only in late Proterozoic, but also throughout the Paleozoic and Mesozoic, and within some of them (Circum-Pacific and Mediterranean belts) even in the Cenozoic. Hence these belts play a different role in the structure and history of the continental crust.

Each of the major belts is divided into sections stretching parallel to the long axis of the belt, their geosynclinal cycles ceasing at different times.

In the Ural-Mongolia belt, geosynclinal areas were initiated at different times. Some of them have developed in the oceanic crust perhaps since the consolidation of the basement of the adjoining ancient platforms, that is,

since middle or even early Proterozoic time, others originated in late Proterozoic, and still others much later, partly in the previously formed continental crust and partly in the residual oceanic crust in between. These areas differ much from each other not only in age, but also in the duration of the geosynclinal cycle.

In those sections of the Ural-Mongolia belt where massifs of granitic and metamorphic rocks consolidated in the middle of the Riphean, new systems of geosynclinal troughs began to grow in the late Riphean to give rise to Caledonian fold areas. Some of the troughs were initiated directly in the oceanic crust, rather than in ancient massifs, but in both instances their systems developed along roughly the same lines.

The systems of troughs were restricted to deep-seated faults resulting from the breaking-up of the oceanic or the already present early continental crust. This was accompanied by lateral faulting or pushing the crustal blocks aside to form huge cracks or yawning gaps in the crust along which systems of geosynclinal troughs appeared. They further evolved according to the general scheme of the geosynclinal development treated in the previous chapter. However, although the succession of the two principal stages of the geosynclinal cycle and that of sedimentation, magmatism, and folding are commonly the same for the geosynclinal areas of different ages, no two areas exist, of course, that could be called identical.

Two types of the Caledonian fold areas are recognized in the Ural-Mongolia belt. Some of them, somewhat older, are named early Caledonian (or Salairian). They most likely began to develop in the oceanic crust early in the Riphean. Their main, geosynclinal stage lasted throughout, or through most of, the Riphean to late in the Cambrian or early in the Ordovician, whereas the orogenic stage took place in Ordovician time. The early Caledonian fold area fringes the Baikalian fold area of the Baikal region and the northern part of the Eastern Sayan on the south and embraces the Kuznetsk Alatau, the southern part of the Eastern Sayan, and the adjacent part of Northern Mongolia.

To the south and southwest, the strip of the late Caledonian (or Caledonian proper) fold area comprises the Western Sayan and Altai and extends through North Mongolia into Central Mongolia. The other late Caledonian area, the Kokchetav-Kirghizia, has an arcuate shape and is in the middle of the belt, stretching from Central Kazakhstan to Kirghizia. Their geosynclinal troughs originated in the middle of, or early in, the late Riphean. Their main stage lasted till the beginning of the Silurian, inclusive. The rocks were then folded, uplifted, and invaded by granite intrusions. These processes marked the onset of the orogenic stage which ended at the beginning or in the middle of the Devonian.

A vast Hercynian fold area occupies the belt between the above Caledonian areas, that is, within East Kazakhstan, the Balkhash region, the Southwestern Altai, and the very long strip of Southern Mongolia. Another Hercynian area includes the entire Urals and extends southeastward into the Southern Tien Shan mountains.

In these areas, the initiation of geosynclinal troughs occurred much later than in the Caledonian areas, namely, in the Cambrian and Ordovician, and in some regions even later. In the Urals and on the margins of the East

Kazakhstan-Mongolia area, geosynclinal troughs were formed by a breaking-up and pushing-aside of the Baikalian basement. L.P. Zonnenshein has found, however, that in the central part of this area, extensive troughs originated in the oceanic crust, a relic of the most ancient crust which survived here until early Paleozoic, occasionally middle Paleozoic time.

In the Hercynian areas, the main stage continued throughout the Silurian, Devonian, and Early Carboniferous. Then the orogenic stage began in the middle of the Carboniferous, after uplifting and folding, with prevailing vertical movements. It came to a close late in the Permian, in some places even in the earliest Triassic. Mongolia also includes younger geosynclinal systems in which, for example, in the Solonker trough, according to L.P. Zonnenshein, the geosynclinal cycle spans the time interval from the Carboniferous or the end of the Devonian to the beginning of the Triassic.

By the end of the Paleozoic-beginning of the Triassic, the geosynclinal cycle had on the whole ended in the Hercynian fold areas. Its time interval is different for different areas in the Ural-Mongolia belt. Hence the basement of the platform within this belt formed gradually. The process began with the generation of separate metamorphic massifs in the middle Proterozoic and in the middle of the Riphean. During the Baikalian folding, the granitic-metamorphic complex formed over great territory within the belt.

Then the process continued in the Caledonian areas until the middle of the Devonian. Finally, the last event was the Hercynian folding, with metamorphism and granitization spreading over almost the entire Ural-Mongolia belt.

In the Atlantic belt, particularly in those of its regions that have survived on the Atlantic coasts of America and Europe, the Caledonian fold areas play a prominent role. One of them comprises the Scandinavian Mountains, Spitzbergen, Scotland, Ireland, and Wales. It was initiated in an oceanic crust in the middle of the Riphean, and its main, geosynclinal stage lasted till the beginning of the Silurian. The Silurian and Early Devonian witnessed the orogenic stage during which mountain areas and intermontane basins formed and thick molasses were deposited, particularly Red Beds and conglomerates of Great Britain, with volcanic rocks in some places. The geosynclinal cycle ceased in the middle of the Devonian.

Very similar was the development of the Caledonian fold area extending from the eastern coast of Greenland through Newfoundland and the eastern coast of Canada and the USA, where it includes the northern Appalachians, to about the latitude of New York. Southward, the Caledonian fold area is followed by the Hercynian, which on the whole began to form at the same time (at the end of the Riphean), but whose main stage ended much later—early in the Carboniferous. Its orogenic stage lasted from the Middle Carboniferous to the end of the Permian.

The Caledonian and Hercynian fold areas of the Appalachians fringe the North American platform on the east and turn around its southern edge. Then they run along the Gulf Coast to Mexico. The continuation of these areas makes up not only the basement of the Florida and Yucatan Peninsulas, where it is overlain by the flat-lying sedimentary cover, but also the bottom of the intervening part of the Gulf of Mexico and encompasses the Mexican Coast.

In summary, parts of the Atlantic belt—the American and European—both ended their geosynclinal development in the middle or at the end of the Paleozoic and were transformed into the basement of young platforms. In the Paleozoic, they probably constituted a single geosynclinal belt separating the North American and East European platforms. It was parted in two later, following the appearance of the Atlantic basin.

According to the literature, within the Arctic belt of the Northern Canada islands, fold areas and the basement of young platforms evolved along the same lines as in the Ural-Mongolia belt, with the end of the cycle also late in the Paleozoic.

HISTORY OF THE MEDITERRANEAN FOLD BELT

The Mediterranean belt is readily subdivided into two parts differing in structure and history: the larger, western one, embracing southern Western Europe, the Mediterranean and Black Sea coasts, the Caucasus, Asia Minor, the Plateau of Iran, Afghanistan, the Himalayas, and the Indochina Peninsula, and the smaller, eastern one, comprising the islands of Indonesia and the intervening seas.

In the western Mediterranean belt, the early phases had some features in common with those in the Ural-Mongolia belt. During the Riphean, which is still largely shrouded in mystery, geosynclinal systems developed here apparently in the oceanic crust. The result was a pre-Paleozoic basement whose remnants are numerous median masses built up of metamorphic and igneous rocks. These masses survived in the western part of the belt, being restricted to the interior of all Paleozoic and Alpine fold systems. The metamorphic basement of the median masses is at places exposed, but it is more frequently overlain by a relatively thick sedimentary cover. In Iran, Asia Minor, and the Caucasus, it formed in the middle of the Riphean (about 1 000 million years ago), and in France and Spain, somewhat later (about 700 million years ago).

Systems of geosynclinal troughs originated in the old (pre-Paleozoic) basement; they evolved like the Hercynian fold areas. The main geosynclinal stage began in Ordovician or Silurian time and continued to the beginning of Carboniferous time. The troughs were then filled with sedimentary and volcanic rocks later intruded by igneous rocks and folded. A platform-type sedimentary cover whose thickness was not large accumulated on many medium masses separating geosynclinal troughs. The orogenic stage then came; it had lasted from late in the Carboniferous through the Permian. The result was large intermontane and marginal basins many of which contain thick coal measures.

After this stage, the Mediterranean belt was highly uplifted and weared down to form vast plains.

The margins of the Mediterranean belt near the edge of the East European platform, which are now occupied by the Scythian sediment-covered platform, all of GDR and FRG southwest of the ancient East European platform, France, the Iberian Peninsula (except for the Pyrenees and Southern Spain), and

the strip of the Atlas Mountains in North Africa, consolidated at the end of the Paleozoic (Late Carboniferous through Permian) to produce the basement of a young epi-Hercynian platform on which a sedimentary cover began to accumulate. Only the narrow middle portion of the belt, within the present-day Alpine fold area, was again involved in geosynclinal development early in the Mesozoic.

Here, new systems of narrow geosynclinal troughs began to grow between the end of the Triassic and the beginning of the Jurassic. They originated along the deep-seated faults that cut across the basement of the Baikalian massifs or broke up the Paleozoic fold structures just formed. The new geosynclinal troughs mainly inherited the trends of the Paleozoic geosynclines, as is well seen in the Greater Caucasus, Alps, Western Carpathians, North Africa, and other regions. But in other places the Mesozoic geosynclinal troughs formed just in the Baikalian crystalline massifs. In all the regions, however, wrench faulting or pushing-aside the blocks of the crystalline massifs made their edges move in opposite directions, and narrow and deep fissures, geosynclinal troughs, appeared in-between. Rocks of the basaltic layer or, perhaps, the mantle protruded to the bottom of many of them.

Two phases of trough generation are recognized in the Alpine geosynclinal area. The older troughs were initiated between late in the Triassic and early in the Jurassic (troughs of Alps, Dinaric Alps, Greater Caucasus, and others). The younger ones began to be delineated by faults only early or late in the Early Cretaceous (in Hauterivian or Aptian-Albian). The main stage of the geosynclinal cycle, marked by the deposition of thick sediments in the troughs, lasted from the Triassic or Early Cretaceous to the end of the Eocene or to Oligocene. It was characterized by volcanism, intrusions of different compositions, and several folding epizodes. The orogenic stage began in the Alpine fold area in Eocene time or late in Oligocene time (at somewhat different times in different areas). Mountain ranges rose and at the same time systems of intermontane and marginal basins originated to be filled by molasse. The central part of the area was cut by many major faults along which new chains of small volcanoes and also large volcanic cones appeared. These include the magnificent extinct volcanoes Elbrus and Kazbek, USSR; Great Ararat and Little Ararat, some volcanoes in Turkey and Iran and the active volcanoes in Italy, on the Aegean Islands, and in many other places.

Plutons invaded at that time. Yet no large young granite intrusions of Neogene and Quaternary age are present in the Alpine fold area; vein-type bodies predominate, as do laccoliths or small bodies of granitic rocks restricted to faults (Central Alps and Greater Caucasus). In most instances, however, the small bodies are undoubtedly outgrowths from larger granite massifs occurring at depth. Dikes and small intrusions worked their ways upward from their respective magma chambers through faults. Their composition supplies information on large granite bodies lying at depth. It is highly probable that they had not fully solidified in Neogene time, and parts of the plastic unconsolidated melt may have survived until Quaternary time. At that time these were sources of volcanic outpourings. Moreover, some of them have retained their state until now.

In the Alpine geosynclinal area, the geosynclinal cycle has mainly ended. Only the orogenic stage may be still going on to some extent. The Alpine area

is now still mobile. Earthquakes often occur there, and mountain ranges are growing, as indicated by the character of mountains deeply dissected by river valleys, systems of river terraces seen on the slopes of mountains, and many other physiographic features. In addition, there are manifestations of subsidence and sagging within some of intermontane basins and grabens. We may say, therefore, that although the folding has mainly come to an end there, that area is still tectonically mobile.

Hence it seems highly plausible that still plastic, unconsolidated, and thus active magmatic granite bodies occur beneath the greatest mountain ranges: the Alps, Greater Caucasus, Western Carpathians, and others. An increased heat flow and hot mineral springs in many regions of the Caucasus and Italy support this view.

INLAND SEA BASINS AND THE INDONESIA AREA

A distinctive feature of the Alpine fold area, probably attributed to its tectonic activity, is the presence of a system of deep crustal depressions in its interior or on its margins, occupied by inland seas. These are the deep sea basins of the southern Caspian Sea, Black Sea, Sea of Marmara, Ionian Sea, Tyrrhenian Sea, eastern Mediterranean Sea, and others.

All these basins are very similar in topography, structure, and probably in mode and time of formation. They have flat bottoms at depths between 2 000 and 3 500 meters, in some places down to 4 000 meters, surrounded by a clear-cut continental rise. According to geophysical evidence, no granitic-metamorphic layer is present beneath the sea floor; it occurs only beneath the margins of the basins. A basaltic layer immediately underlies the pile of sediments whose thickness reaches 10, 15, and occasionally 20 kilometers. That the sedimentary column is very thick can be explained by the fact that these basins are surrounded by continents and islands and thus receive much more debris than the vast expanses of the ocean floor. The sea basins are, therefore, natural traps for bottom sediments which are supplied from land and gradually fill these basins.

The edges of the Ligurian, Tyrrhenian, and Ionian basins cut off the land structures and are thus younger. Moreover, much data, particularly paleogeographic, suggest that the Tyrrhenian basin originated at the site of an earlier uplifted crystalline massif.

The deep basin of the Black Sea, which occupies its greater, southern part, may also be young. The data available on the surrounding land indicate that the area of the Black Sea floor was occupied in Mesozoic time by the following geosynclinal troughs: the Crimean-Caucasian of Triassic-Middle Jurassic age in the north and those of Cretaceous age in the south, in the area adjacent to the Pontian, northern Asia Minor. In the central part of the sea, between these troughs, a median mass occurred as a continuation of the Transcaucasian (Georgian) median mass, which was partly or fully covered by sediments deposited in a shallow sea. Fold mountains rose late in the Eocene, and the Black Sea-Caspian Sea basin became isolated from the Mediterranean basin. Since then the Black Sea basin has existed as an entity.

Here, several orogenic basins formed in the Oligocene, at the time when the Caucasus, Balkan Mountains, and other mountain ranges began to rise. They were filled with thick molasse.

The present-day Black Sea basin has a flat floor with a depth about 2 000 meters and a clear-cut continental slope fringed by the shelf. Its edges cut off the surrounding mountain ranges. It has swallowed up the margins of the Asia Minor coast, and the mountains that earlier connected the Pontian with the southern Balkan Peninsula within Bulgaria. The vast southern half, if not more, of the Crimean Mountains has also disappeared, as have some of the fold structures within the coast of the Northwestern Caucasus.

All the above indicates that as time passed the Black Sea basin was greatly enlarging its area at the expense of the surrounding coasts.

It has been determined by seismic techniques that up to 15 kilometers of sediment has been deposited on the floor of the Black Sea basin. The sequence is subdivided into three series differing in density and longitudinal seismic wave velocities. The upper series, up to 2 kilometers thick, appears to comprise the youngest, Quaternary, and Middle and Upper Pliocene sediments; the intermediate series, up to 5 kilometers thick, consists of the lowermost Pliocene, Miocene, and Oligocene and fills orogenic basins; and the lower series is composed of Eocene, Cretaceous, and at places Jurassic rocks. This sedimentary veneer of the Black Sea median mass was laid down in a shallow sea that covered it from time to time. The intermediate series was probably deposited in a system of orogenic basins within the present Black Sea floor, which originated during the Alpine orogenic stage (Oligocene through Neogene). The upper series is more extensive and overlaps the lower two series. Along the Black Sea margin, it onlaps older strata resting on their eroded surface. Its occurrence can thus be related to the widening and deepening of the Black Sea floor since the middle of the Pliocene. The deposition of this series was accompanied by the formation of the modern deep basin of the Black Sea (Fig. 27).

We may conclude, therefore, that the basin under discussion is extremely young, namely, 4.5 or 5 million years old. Attention should be directed to the great thickness (up to 2 km) of the youngest series, which accumulated for so short a period. Furthermore, the Black Sea basin is about 2 kilometers deep. The thickness of the Pliocene-Quaternary series and depth of the depression of the Black Sea both indicate that the basin floor has sunk some 4 kilometers since the middle of Pliocene time. Thus the average rate of subsidence was about 1 mm per year.

It has recently been found (R. Selli and A. Fabbri) that the Tyrrhenian Sea basin is of the same age. According to dredging results, the floor of the basin is underlain by Pliocene-Quaternary sediments containing foraminifers and reaching 900-1 000 meters in thickness. As in the Black Sea, these overlap a wide range of older strata, indicating considerable widening of the Tyrrhenian Sea basin. Therefore, this basin has also formed since the middle of the Pliocene and downbuckled rapidly, like the Black Sea basin.

As distinct from the Black Sea, the sagging was accompanied here by deep faulting, the faults serving as passageways for volcanic products that were erupted on to the surface and generated the volcanoes of the Lipari Islands, the Vavilov volcano on the floor of the Tyrrhenian Sea, Vesuvius, and others.

The radiometric age of the lavas is nearly 1 million years, whereas the initiation of the basin is dated at 4.5 million years. The Black Sea basin is, therefore, very similar in age to the Tyrrhenian Sea basin. This makes us believe that the other Mediterranean basins, in particular the Western one, between the coasts of France, Algeria, Corsica, and Sardinia, resemble each other as to the time and mode of formation.

A shallow sea basin existed in Miocene time where the vast Western basin is now. Messinian rock salt, tens or even hundreds of meters thick, shallow-sea limestone, shale, and sandstone accumulated on its floor late in the Miocene. The present-day deep-sea basin with the flat floor lying 2 000 to 3 000

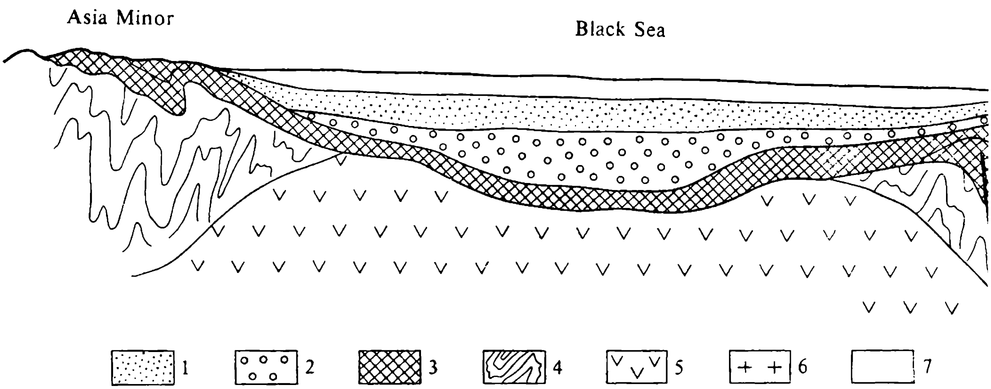


Fig. 27. Diagrammatic cross-section of the hypothetic Black Sea floor:

1 — Quaternary and Upper Pliocene sediments;
2 — Oligocene and Miocene sediments of orogenic troughs;
3 — Eocene, Paleocene, Cretaceous and Jurassic sediments of the Crimean Mountains and those supposed in sedimentary mantle of Black Sea median mass;
4 — folded metamorphics of late Proterozoic and Paleozoic age in basement of Scythian

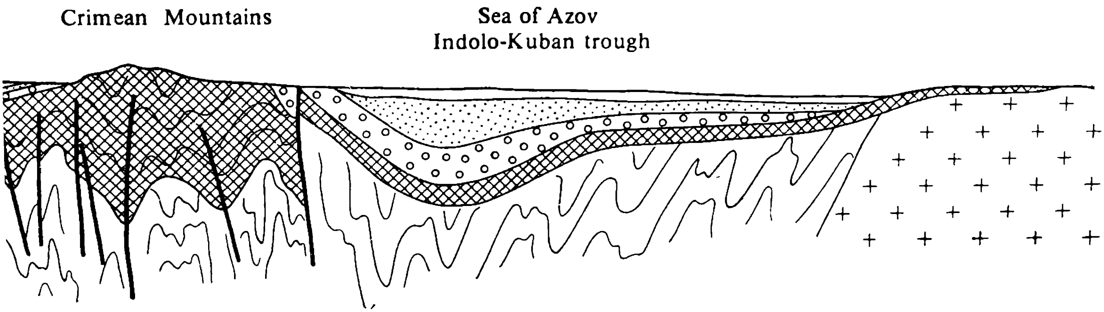
meters below sea-level was derived from subsidence in Pliocene and Quaternary times. The rapid floor sinking was accompanied by salt uplifting—the formation of numerous salt domes now discovered by geophysical methods and drilled through.

All the basins of the Mediterranean, Black, and Caspian seas appear to be the result of large-scale sinking at approximately one time due to the compaction of the deep interior of the earth's crust very soon after the Alpine folding.

In trying to solve the problem of the origin of the Black Sea, many scientists (S.I. Subbotin and others) have concluded that the compaction might have been there due to metamorphism in the interior of the crust, with the resulting transformation of the basaltic layer into rocks of the metamorphic eclogite facies which is identical in density with the mantle material. At the same time, the granitic-metamorphic layer apparently changed into rocks of the granulite facies. Owing to compaction, the lower parts of the crust shrank, its surface subsided, and deep basins formed. Some basins, not yet very deep (Alboranian, and those of the Sea of Marmara and Adriatic Sea), are at the beginning or in the early stage of this process.

There are other hypotheses explaining the origin of these basins. Thus A.V. Peive, E.E. Milanovsky, and others consider them the remnants of the ancient oceanic crust, and the French scientist L. Glanjeaud considers them the areas where the granitic-metamorphic layer was pushed aside and the basaltic layer was exposed and later overlain by sea-bottom sediments.

Clearly, the problem of the Mediterranean basin and those of other inland seas is extremely interesting, and new data will undoubtedly be obtained in the near future that will shed light on the circumstances under which these basins originated and evolved. The only certainty is that they are closely related to the young Alpine geosynclinal area which is still active.



sediment-covered platform, Crimean Mountains, and Asia Minor;
5 — layer underlying sedimentary sequence beneath Black Sea floor (geophysically detected "basaltic layer");
6 — basement of ancient East European platform;
7 — water

The eastern part of the Mediterranean belt, where the Indonesia area is situated, differs essentially from the western part in that no older basement ever appeared within its limits, and the Indonesian fold system formed and is developing entirely in the oceanic crust.

Within Indonesia, the geosynclinal cycle may be in a much earlier phase than within the Alpine area. This area consists of several chains of large and small islands which extend along the uplifted mountain ranges separated and bordered by narrow troughs and sea basins. These are modern geosynclinal troughs filled with marine sediments and submerged.

In eastern Indonesia, the mountain ranges around the Banda Sea basin are essentially drowned, and only their topmost parts rise above sea-level as lines of small islands and reefs. In the central part of the Malay Archipelago, sea mounts are crowned with fairly large islands (Flores, Sumba, Sumbawa, Lombok, and Bali). Farther to the west, the largest islands, Java and Sumatra, and others are the visible summits of the mountain system that grows from the sea floor (Fig. 28).

This system is variable in height. And a single fault zone extends its entire length and marks a chain of numerous volcanoes running through all the

islands of Indonesia from the Banda Sea to northern Sumatra. Fifty five volcanoes are active on Java alone.

The islands of the Malay Archipelago are geologically several anticline-type uplifts inside a fold area, which are separated by narrow trenches and depressions of the sea floor representing geosynclinal troughs.

Thus we have here a geosynclinal area rather early in its life. The large islands of western Indonesia are likely in their final stages, with the uplifts involving vast areas. The eastern part—the islands around the Banda Sea—is much earlier in its evolution and has no large uplifts. We see here a typical island arc.

The geosynclinal troughs of the Alpine fold area were initiated in Paleozoic and Mesozoic times in the continental crust that originated in the Riphean during the Baikalian and middle Riphean foldings.

Two major tectonic cycles are distinguished in the Hercynian fold areas of the Mediterranean belt: the Riphean and Hercynian; the Alpine fold area is characterized by three cycles: the Riphean (Baikalian), Hercynian, and Alpine. In the end, a continental crust of great but varying thickness emerged. The generation of inland sea basins leads to its further transformation.

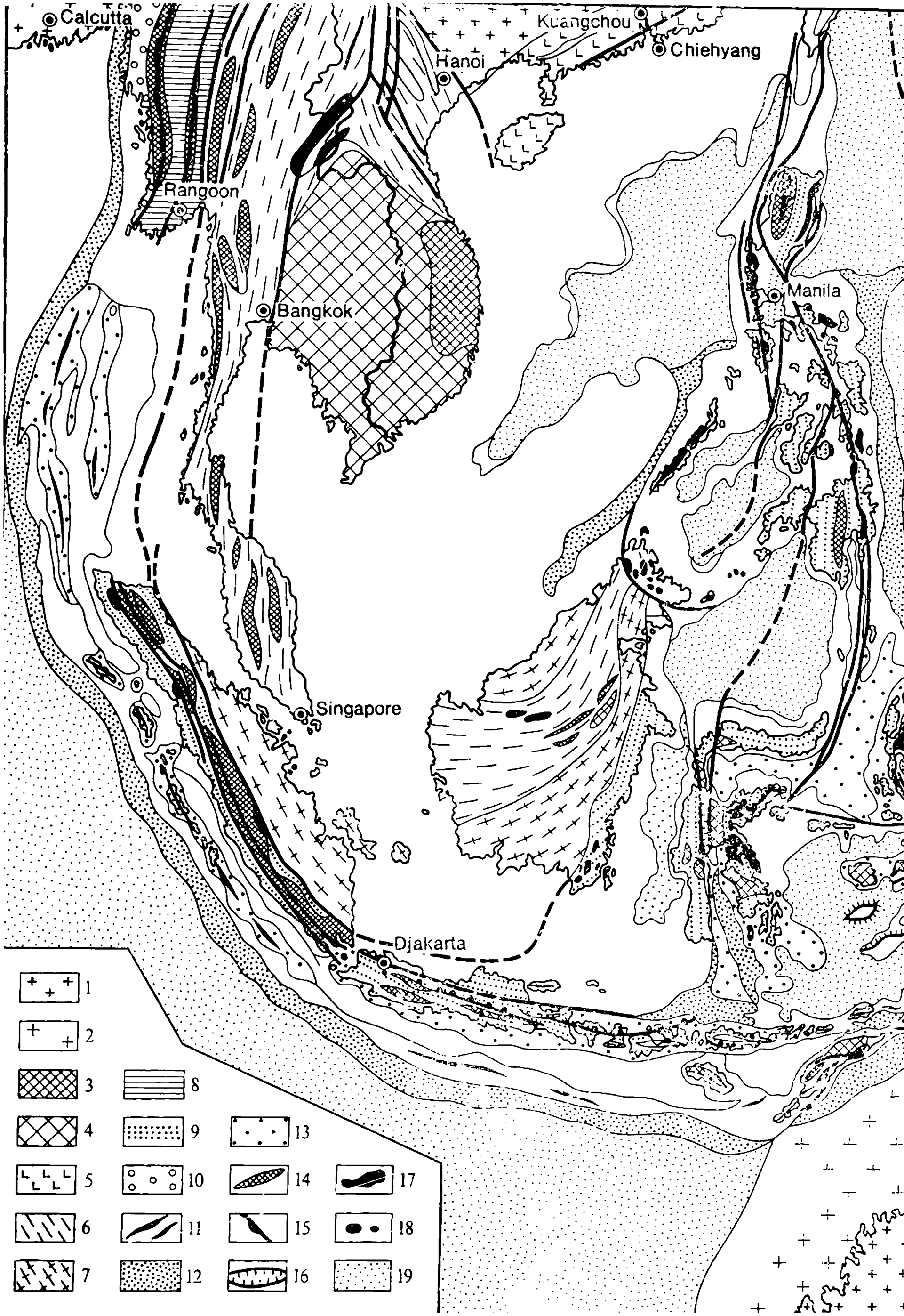
HISTORY OF THE CIRCUM-PACIFIC BELT

The Circum-Pacific belt differs greatly in its geologic history from the other belts. The belt encircles the Pacific floor and separates it from the ancient platforms of Asia, Australia, Antarctica, and South and North America. Accordingly, it is extremely asymmetrical. Its component fold areas developed successively from its periphery inward.

The oldest, late Proterozoic and Paleozoic fold areas of the belt are located near the very edges of the ancient platforms in Australia, Antarctica, and Southeast China. The areas whose geosynclinal cycle ended in the Mesozoic are spread wider; these are the Verkhoyansk-Chukot area in Siberia, the Rockies in North America, the Andes in South America, and the Antractic Peninsula in the Antarctica. Then the Cenozoic areas occupy separate segments of the belt in America, Asia, and Oceania, and finally, the inner zone is composed of the youngest, still evolving geosynclinal areas on the margins of the Asian and Australian continents, in Central America, between America and Asia (Aleutian arc), and between America and Antarctica (arc of South Sandwich Islands).

The late Proterozoic (Baikalian) and Paleozoic fold areas of Australia are east of the ancient Australian platform. The Baikalian fold area of Adelaide, Australia, was initiated in the ancient lower Proterozoic continental crust in the west and in the oceanic crust in the east. It developed till the very end of the Riphean. Its folding and granite intrusion took place early in the Cambrian.

The new Tasmanian system of geosynclinal troughs appeared in Paleozoic time farther to the east within Australia. Some of them formed in the Baikalian continental crust on the margin of the Adelaide area, the others farther eastward, in the oceanic crust. Spilitic lavas and tuffs deposited in these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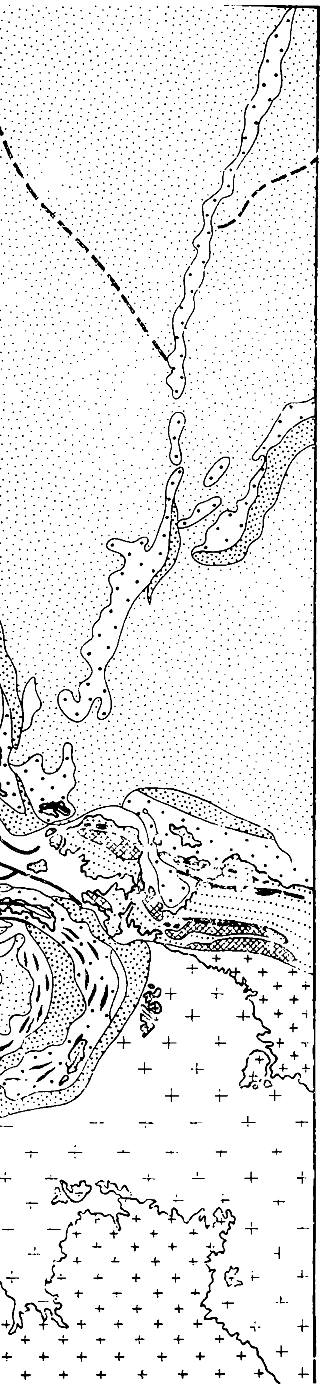

Fig. 28. Diagrammatic map showing the ocean floor physiography and the tectonics of the islands of Indonesia.
Platforms and fold areas of different ages:

1 — ancient platforms;
2 — same below sea level;
3 — outcrops of basement of young platforms and median masses;
4 — same buried beneath sedimentary cover;
5 — Caledonian fold areas;
6 — late Paleozoic-Mesozoic fold areas of northern Indochina, Burma, and Malay Peninsula;
7 — same buried under sedimentary cover (Sumatra and Kalimantan);
8 — late Cretaceous and Paleogene fold areas;
9 — Neogene fold areas of Sumatra, Java, and other large islands;
10 — Neogene foredeep;
11 — anticlines;
12 — deep-sea trenches and their continuations on land;
13 — rising anticlinal uplifts (island arcs);
14 — anticlinorium, large anticlinal uplift;
15 — deep-seated fault;

Structural and topographical features;
16 — grabenlike trough;
17 — protrusion of ophiolitic complex of ultrabasic and basic rocks;
18 — major volcanic cones;
19 — floors of deeps and continental slope

troughs in Cambrian time, and clayey-sandy rocks alternating with volcanics, from Ordovician through Silurian times. They were folded and uplifted in the middle of the Devonian, which marked the end of the main stage in the geosynclinal cycle.

The troughs of the orogenic stage subsided in Devonian time. To the east, however, on the coast of Australia, the main stage continued till early in the Carboniferous, and the orogenic stage, with its inherent granite intrusions, started late in the Carboniferous.

Therefore, near the Adelaide fold area of Baikalian age, the Tasmania fold area of the Caledonian type originated, whereas to the east, along the coast, this fold area is of the Hercynian type. A system of troughs and island arcs began to form on the oceanic crust early in their development in Cambrian time. The geosynclinal process gradually extended eastward, involving the neighboring part of the ocean floor.

Evidence is available (N.A. Bogdanov) that similar island arcs were generated in Paleozoic time in New Zealand, New Guinea, and New Caledonia. Here, however, the fold systems evolved for a longer time, and they made up the crust underlying younger fold systems occurring within these islands and belonging to the region of the Cenozoic folding.

In Catasia, Southeast China, near the edge of the South China platform, a fold complex appeared in the Proterozoic and developed until the middle of the Riphean (900-1 000 million years ago). In the resulting continental crust, a system of geosynclinal troughs was initiated and then filled with sedimentaries and volcanics from late in the Riphean to early in the Paleozoic. The main stage of the geosynclinal cycle ended before Devonian time. In the Devonian, troughs of the orogenic stage formed and were filled with molasse red beds. In summary, the Catasia area is of the Caledonian type.

The history of Mesozoic geosynclinal areas, whose development ended in the Cretaceous, was much longer and more complicated. The Cordillera area, North America, is the longest of them; it extends from Alaska through Canada and the USA across almost all of Mexico. Several different sections can be recognized within its limits to illustrate the general trend in the development of the areas of the Circum-Pacific belt.

In the eastern part of the area, a broad fold strip appeared early in late Proterozoic (Riphean) time running along the edge of the North American platform. Here, the folding and intrusive activity were terminated in the middle of the Riphean to produce the continental crust about 1 000 million years ago. In the late Riphean (750-800 million years ago), a system of geosynclinal troughs was initiated in this continental crust and then filled till Carboniferous time with thick clayey-sandy and carbonate (limestone and dolomites) sediments. Farther to the west, they are becoming thicker, and volcanic series appear in the sequence.

West of this region, beyond the limits of the early Riphean basement, a system of two large uplifts began to grow at the end of the Riphean on the oceanic crust. They grew along faults with an intervening downwarp and were actually island arcs, that is, chains of island stepping stones crowned with a great many volcanoes while the downwarp was a deep geosynclinal trough filled with late Riphean, Cambrian, Ordovician, Silurian, and Devonian vol-

canic and sedimentary rocks. Their thickness is great; the Silurian alone is up to 7 000-9 000 meters thick.

At the end of the Paleozoic, a new trough was initiated farther to the west in the oceanic crust. According to N. A. Bogdanov, it was analogous to the present deep-sea trenches near island arcs. From the Carboniferous through the beginning of the Triassic, the trough was filled with extremely thick spilitic and andesitic lavas, tuffs, and sediments, with basic and ultrabasic ocean-floor rocks at the base.

Finally, still farther to the west, another trough began to form at the end of the Jurassic; it sagged and was also filled with thick siliceous and volcanic rocks of the Fransiscan series until the end of the Cretaceous.

It is clear, therefore, that as time passed, each geosynclinal trough was initiated successively farther to the west within the Rockies. And each time the trough was underlain by the oceanic crust, the adjoining area of the ocean floor being gradually involved in the geosynclinal cycle. The sediments of the same age as those filling these geosynclinal troughs, that is, not only Paleozoic, but also Triassic and Jurassic, also occur in the Cordillera to the east; however, their thickness is not great there, and no volcanic rocks are present.

The Rocky Mountains area is usually divided into a eugeosyncline in the west, with much volcanism, and a miogeosyncline in the east, without volcanism.

The main folding took place during the Nevadan era (Late Jurassic-Early Cretaceous), and the orogenic stage, with the formation of an extensive foredeep in front of the Rockies, during Cretaceous time. The final Laramide folding is assigned to the end of the stage, that is, to the Cretaceous-Paleogene boundary. The uplifts of this stage are associated with huge granite batholiths occurring in a belt that parallels the Cordillera and Sierra Nevada and then runs through Idaho, USA, into Canada.

In the orogenic stage, the major uplifts also involved the strip of the North American platform that adjoins the Cordillera. Here, the earth's crust was cut by faults into blocks and each of them was variously upfaulted or downfaulted. The overlying rocks of the sedimentary cover were in some places folded, cut by faults and even overlapped by blocks shoved toward the platform. Therefore, the Rocky Mountains fold area essentially includes the margins of the ancient platform.

The South American Andes differ greatly from the North American Cordillera. Above all, as yet no geosynclinal systems have been known to develop here in the oceanic crust. Within the Andes, the Mesozoic fold areas occur only in their middle stretch including Peru, Bolivia, and northern Chile; the northern and southern Andes belong to the Cenozoic fold areas. Within the middle Andes, the ancient South American platform is margined by a Paleozoic fold area whose geosynclines were initiated in the older, perhaps upper Proterozoic crust. The geosynclinal cycle of this area ceased at the end of the Paleozoic, that is, at the beginning of the Hercynian folding epoch.

Toward the ocean, a younger system of troughs appeared in the Paleozoic continental crust. Its geosynclinal stage extended from the Triassic through the Jurassic; hence it can be assigned to the Mesozoic fold area. At the end of the Jurassic, the system was involved in the Andean folding with the forma-

tion of the rather gentle fold structures of the Andes. Then came the orogenic stage. A very long trough originated and was filled mainly with terrestrial andesites and tuffs of Cretaceous age. According to M.G. Lomize, their thickness exceeds 10 600 meters. These rocks were at the same time intruded by extremely elongate batholiths extending hundreds of kilometers along the Andes. The present mountain topography of the Andes is attributed to later uplift during Neogene time.

A fairly complex fold area occupies the Antarctic coast which borders the Pacific on southern side and includes the Antarctic Peninsula, Ellsworth Highland and Marie Byrd Land. According to G.E. Grikurov, who participated in the latest investigations carried out in the Antarctica and has summarized the data available, the base of the sequence of rocks underlying the area is composed of the folded Rossian complex of Riphean and Cambrian age. It is analogous to the Baikalian complex and is intruded by granites. The troughs are filled with Carboniferous, Permian, and Triassic series which compose the main geosynclinal column. These are overlain by Lower and Upper Cretaceous molasse of the orogenic complex, which is invaded by granites about 100 million years old. Thus we get here a fold area whose age is similar to that of the middle Andes.

The fourth Mesozoic fold area of the Circum-Pacific belt is called the Verkhoyansk-Chukot area. It is similar to the above areas in time of folding cessation (in the middle of the Cretaceous) and of granite emplacement, but was initiated later. The extensive western part of the Verkhoyansk-Chukot fold area began to form in the thick folded and metamorphosed continental crust, apparently the margin of the Siberian platform. Geosynclinal troughs appeared at the end of the Paleozoic or in the Triassic. The main stage continued through the Triassic into the Jurassic. The area entered the orogenic stage between the end of the Jurassic and the end of the Early Cretaceous.

The other, quite different part, the Alazeysk-Oloy, has recently been found east of the above fold area. It was earlier referred to as the eastern half of the Kolyma Massif, or platform. According to S.M. Tilman, the area is occupied by a deep geosynclinal trough filled with volcanic and sedimentary series of siliceous rocks, spilites and andesites of Middle and Late Devonian age, and with a flysch series of earliest Carboniferous age. All of them are folded and intruded. Their eroded surface is overlain by Permian conglomerate and extrusive rocks followed upward by Triassic and Jurassic rocks. Numerous orogenic troughs are invariably filled with Lower Cretaceous sediments containing some volcanics and coal seams.

After the orogenic stage, the extensive north-eastern part of the continent of Asia, including the Verkhoyansk area, Chukotski Peninsula, and Sea-of-Okhotsk coast; the Rocky Mountains area; and the middle stretch of the Andes were uplifted to form mountain ranges. Although the geosynclinal cycle has ended there and the basement has formed, the sedimentary cover has not yet begun to accumulate on it. All these areas are still mountainous. Some of their parts were uplifted in Neogene or Quaternary times and are now lofty mountain ranges. These have not yet been transformed into true platforms with the basement overlain by the sedimentary cover. All these areas appear to be for a long time in an early stage of the formation

of continental platforms during which the surface is highly elevated and volcanism is violent.

The Cenozoic fold areas encompass the broad inner zone of the Circum-Pacific belt. They can be grouped into the areas whose geosynclinal stage ceased in the Cenozoic, and the longer, occasionally broad strips that are present geosynclinal areas. These can be observed as island arcs and the adjoining sea basins.

In some regions of the Circum-Pacific belt, these two types, which differ somewhat in age, parallel each other. In this case, the areas of the first type are on the periphery within the belt as compared with present-day geosynclines.

These areas differ not only in that some of them have passed through their geosynclinal cycle while others have not, but also in time of initiation of their respective geosynclinal troughs. The age of the troughs in present geosynclinal areas can be established only for some of them and has been found to be Cretaceous or even younger. The areas of the first type are divisible into those whose troughs began to subside in the Paleozoic and developed through the Mesozoic into the Cenozoic and those whose troughs are as young as Mesozoic, for the most part Cretaceous, and evolved till the middle or the end of the Cenozoic. These troughs were initiated in the oceanic crust, but some of them in the older continental crust.

At the same time, both types of fold areas are, as a rule, closely associated with each other and make up parts of the extensive Cenozoic fold areas. The regions where the geosynclinal cycle has been terminated are the marginal strips of the fold areas and frequently occupy only a smaller portion of their territories. Those where the folding is still going on represent a system of ridges (ocean floor highs or island arcs) divided by deeps. The territories along the Asian-Australian stretch of the Circum-Pacific belt are the most extensive.

There are examples, however, of isolated fold areas whose geosynclinal cycle ended in the Cenozoic and that are not associated with island arcs. These are the Sikhote-Alin and the Coast Ranges of the USA.

On many island arcs or large islands and the peninsulas that are closely related to them, such as on the Eastern Kamchatka Peninsula, Taiwan, New Caledonia, and Cuba, thick gabbro, basalt, and ultrabasic (peridotite and serpentinite) complexes similar in composition protrude through major faults. In some places, there is an alternation of gabbro, basalt, and ultrabasic rocks (A.L. Knipper). These are known to make up the basaltic layer of the oceanic crust. Here, these rocks are raised to the surface along faults and form large crustal blocks many of which are found to be somewhat shoved against sedimentary series. Their presence suggests that the geanticlinal ridges of island arcs rose from the ocean floor. The overlying Cretaceous and Paleogene-Neogene sedimentary and volcanic rocks mark the early phases in the geosynclinal cycle.

The Cenozoic fold areas of the Asian-Australian stretch of the Circum-Pacific belt are exemplified in the north by the fold area of the Koryak highlands and the Kamchatka Peninsula. This area originated from a system of geosynclinal troughs that were initiated in the oceanic crust in the middle of Cretaceous time (Fig. 29).

The western anticlinal part of the Kamchatka is a large uplift that has grown from an island arc. Along the axis of the anticline, metamorphic rocks—plagioclase gneiss and glaucophane schist—are exposed at the surface. According to radiometric dates, these are the metamorphosed volcanics and sedimentaries of Cretaceous age. These rocks were lavas, tuffs, siliceous muds, and pure siliceous jaspers. At the end of Cretaceous time, an uplift (underwater ridge) began to grow in the axial part of the structure. Basaltic and andesitic lavas, tuffs, and clastic rocks (breccias) accumulated on its sides. The uplift grew in the Paleogene and Neogene, and lava flows piled up on land, rather than on the sea floor, that is, eruptions took place on an island.

At the eastern Kamchatka, near the uplifted ridge, according to M.S. Markov, a narrow and deep trenchlike trough in the ocean floor collected thick clayey-siliceous sediments and tuffs and some basic (spilitic) lavas. Outside the trench, ocean-type fine-grained and calcareous muds and volcanic tuffs were deposited on the ocean floor.

At the end of the Neogene, the greater part of the Kamchatka was involved into uplift, and the relevant sedimentary and volcanic series were folded to mark the onset of the orogenic stage. In the east of the Peninsula, however, on Cape Kamchatka, sagging and accumulation of sedimentary and volcanic series continued. This part is still an active present-day geosynclinal area and passes directly into the Kuril island arc.

According to M.S. Markov, Cape Kamchatka contains a protrusion (horst) of the oceanic crust overlain by a geosynclinal column. The crust consists of gabbro and ultrabasic rocks that make up the basaltic layer beneath the ocean floor on which both the basin of Cape Kamchatka and the Kuril island arc originated. The arc is a line of ocean-floor highs crowned with islands. The highs are anticlines growing from the ocean floor along faults and associated with numerous active and extinct volcanoes. In a single belt, seven or eight ridges are in *en echelon* arrangement and have been growing since Cretaceous time.

The Kuril system of ridges and the southwestern Kamchatka are fringed on the oceanward side by the narrow deep-sea Kuril Trench, and on the Sea-of-Okhotsk side by the Okhotsk Abyssal Plain. These depressions are both present-day geosynclinal troughs.

The history of the Sikhote-Alin area differs considerably from that of the Kamchatka Peninsula. Its troughs were initiated in the older (Baikalian) folded rocks, and their system originated as far back as Paleozoic time (Devonian or Silurian). Then these troughs intermittently subsided, and sedimentary and volcanic series accumulated throughout the Paleozoic, Triassic, Jurassic, and most of the Cretaceous. Late in the Cretaceous (at halfway through Late Cretaceous) the area was uplifted and folded, and the orogenic stage started in which basic rocks and granites were intruded and violent eruptions of liparite-dacite lava flows took place.

On the Japanese Islands, a system of island ridges and a deep-sea geosynclinal trough also began to develop in middle Paleozoic time in the Baikalian (pre-Silurian) continental crust or just near its southeast edge, in the oceanic crust. They were related to major faults and bisected the would-be Kyushu and Shikoku Islands and then ran along the south-east coast of Hon-


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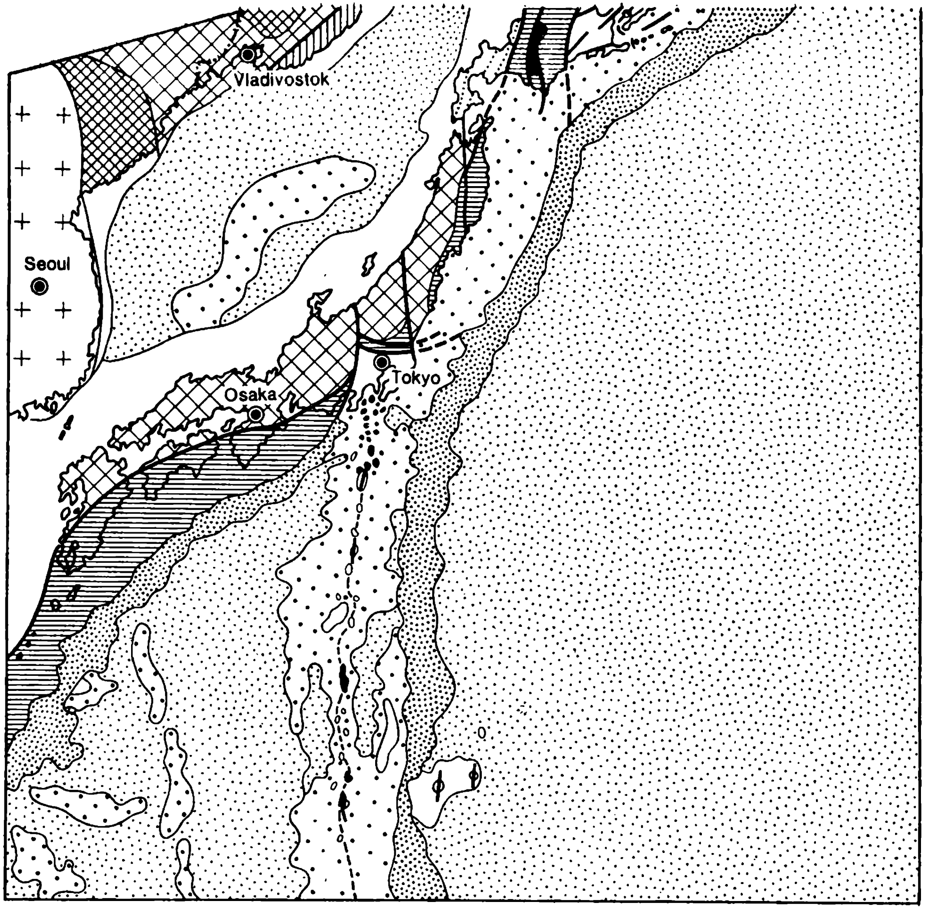


Fig. 29. Diagrammatic map showing tectonic elements of the East Asian segment of the Circum-Pacific belt:

1 — ancient platforms;
2 — same buried beneath sedimentary cover;
3 — outcrops of basement of young (epi-Baikalian) platforms;
4 — sediment-covered young platform ;
5 — Verkhoyansk-Chukot fold area;
6 — Cretaceous-Paleogene fold areas;
7 — Okhotsk-Chukot volcanic belt of Cretaceous age;
8 — Neogene fold areas;
9 — fold systems associated with long-developing (Paleozoic to Cenozoic) geosynclinal troughs;
10 — major anticlines;
11 — deep-sea trenches;
12 — rising anticlinal uplifts;
13 — metamorphic rocks from core of Kamchatka anticlinorium;
14 — deep-seated fault;
15 — graben;
16 — outcrops of ophiolitic complex;
17 — major volcanoes;
18 — floor of deeps in marginal seas and Pacific Ocean

shu Island to east of Tokyo. The trough rapidly subsided till the middle of Permian time, when the contained sedimentary and volcanic layers were folded, metamorphosed and intruded by granites. Since the Triassic and Jurassic, especially during Cretaceous time, the trough, which paralleled the Paleozoic one, actively subsided again, and geosynclinal sedimentary and volcanic rocks accumulated. Large granite massifs invaded these rocks at the end of the Cretaceous, whereas in Eocene time the sedimentary and volcanic rocks were folded, extensively overthrusted, and metamorphosed to glaucophane schist.

The other active zone of sagging and folding originated in Jurassic time in the central part of Hokkaido Island. It continued northward into East Sakhalin. The trough subsided throughout Cretaceous time. In the Paleogene, the layers were folded, metamorphosed and invaded by granite plutons.

South of Japan, a huge present-day geosynclinal area occurs, inluding the Ryukyu and Philippine Islands and Taiwan Island in the west, and the Bonin, Mariana, and the Caroline Islands in the east. Between the ridges lie the vast Philippine and Mariana basins separated by a ridge of seamounts and small islands. Both ridges—the Mariana-Caroline and Ryukyu-Philippine—are fringed on the east side by deep-sea threnches.

Within this region, Taiwan encompasses the area occupied in Neogene time by a large anticlinorium. As on the Kamchatka, its core is made up of Mesozoic and Paleozoic metamorphics.

A major fault extends through all the main islands of the Philippines. It is also the site of several large uplifts built up of probably Mesozoic metamorphics, the oldest on the Philippines and overlain by Cretaceous and here and there by Jurassic sediments, and of massifs of gabbro and basic and ultrabasic rocks. As on Cape Kamchatka, these massifs may be parts of the raised basaltic layer of the oceanic crust in which systems of geosynclinal troughs formed. The oldest sediments deposited in depressions of the ocean floor are assigned here a Cretaceous or Paleogene age and consist of an alternation of thick volcanic and siliceous rock layers (chert, jasper, greywacke, basalt, andesitic tuff, and others). Gneiss and other metamorphics may have been derived from these relatively young volcanic and sedimentary rocks.

The complex structures of the Philippine Islands, which trend north-south east of the above-mentioned major fault and southwestward west of it, are still developing. Here, some of the troughs received between Miocene and Pliocene times enormously thick (up to 6 000 meters) clayey-sandy sediments intercalated with tuffs and lavas. The rocks were then slightly folded early and late in the Pliocene.

Next in the Circum-Pacific belt comes a vast area margined by New Guinea and New Zealand and occupied by numerous arcs and ridges of Melanesia interspersed with sea basins.

On New Guinea and New Zealand, the geosynclinal cycle came to a close mainly in Neogene time, whereas the entire intervening area of the Admiralty Islands, Solomon Islands, New Hebrides, New Caledonia, Fiji Islands, Tonga Island, and Kermadec Islands can be considered a modern geosynclinal area still early in its evolution.

New Guinea is crossed by a long uplifted belt within which green schist and phyllite, large massifs of basic and ultrabasic rocks, and the most an-

cient metamorphics are exposed. These rocks may make up a huge block of the earth's crust shoved southward on the fault plane whose trace coincides with the axis of New Guinea. Exposures can be observed in the thrust sheet of basic and ultrabasic rocks derived from the basaltic layer of the earth's crust and overlain by volcanics and siliceous sediments. This pile is followed upward by not-too-thick Paleozoic (Silurian, Carboniferous, and Permian) series and by a true geosynclinal column of volcanic, siliceous, and greywacke rocks of Jurassic, Cretaceous, and Paleogene age.

Protrusions of the ancient rock complex composed of the basic and ultrabasic rocks of the crustal basaltic layer are traced along the fault zone of New Caledonia and farther along faults through both islands of New Zealand.

Therefore, the geosynclinal troughs and the associated ridges rising from the ocean floor were initiated at the site of New Guinea and New Caledonia as far back as Paleozoic time. Sagging was the greatest in the Mesozoic and Paleogene, and crustal block overthrusting, in the Neogene. The same is true of New Zealand, where the system of geosynclinal troughs began to form early in the Paleozoic, and geosynclinal volcanic and sedimentary rocks deposited during the Paleozoic. Then the geosynclinal development continued in the Mesozoic and ended at the beginning of the Paleogene.

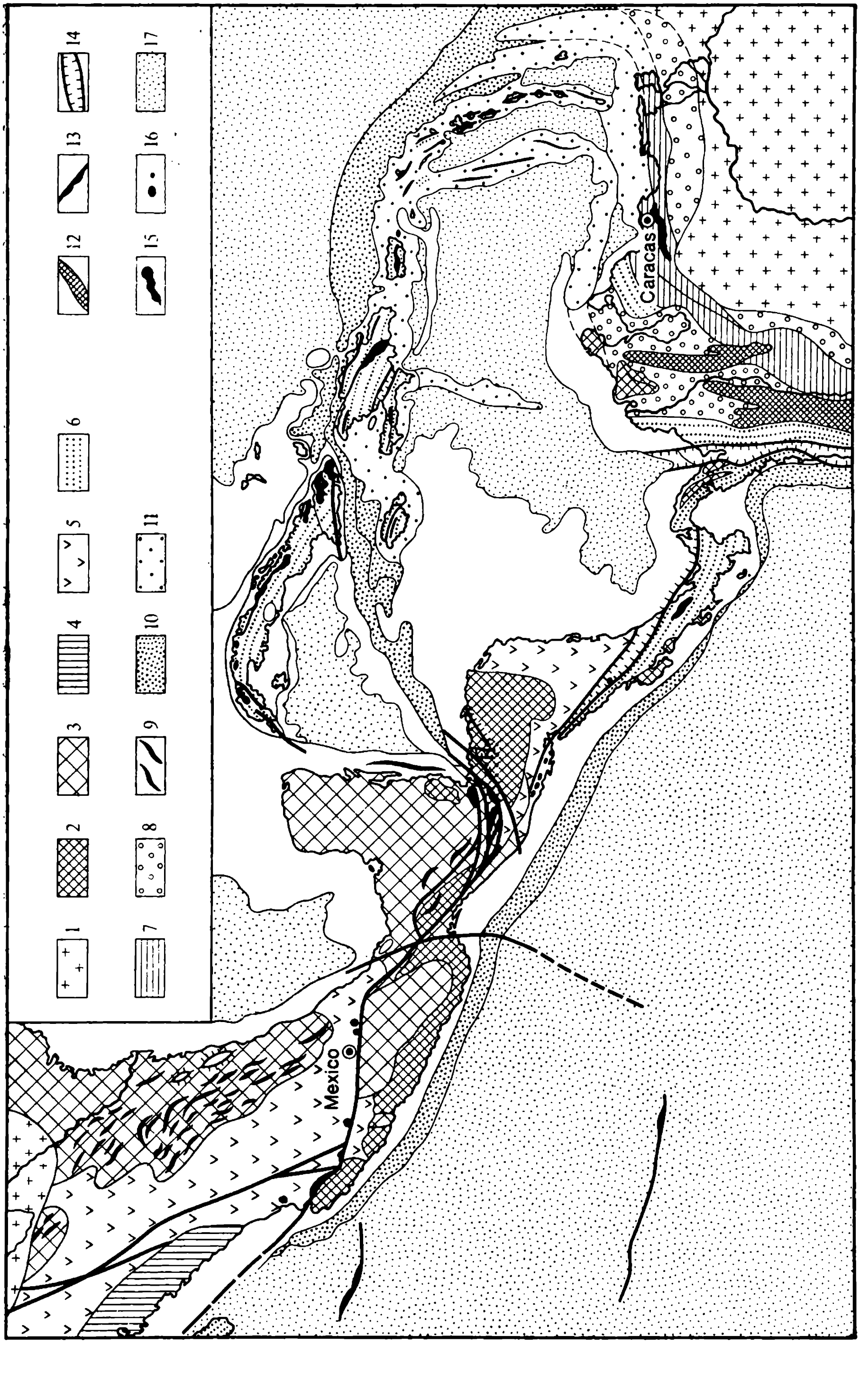
The entire Melanesia between New Guinea and New Zealand is now an active area with considerable andesitic volcanism and great seismicity. It can be subdivided into growing ridges crowned with islands, basins, and deep-sea trenches. The chief ridge, topped by islands, is a chain of island arcs extending from the Admiralty Islands through the New Hebrides and Fiji Islands and farther south to the Colville Rise and the Lau Ridge. The ridge consisting of the Tonga and Kermadec Islands parallels the Lau Ridge and blends with North Island of New Zealand. A system of trenches extends nearly the length of the ridge along its oceanward side. The other series of trenches runs to the west of it, from the Solomon Islands to New Caledonia.

The other ridge composed of islands and underwater highs can be traced from the southeast end of New Guinea to New Caledonia and North Island of New Zealand. Vast sea basins are between the two ridges under discussion—the North Fiji and South Fiji Basins and the basin of the Coral Sea—which are now regarded as present geosynclinal troughs.

The southern end of the area is occupied by the Macquarie Rise and Island located south of New Zealand.

The Aleutian island arc links the Asian-Australian and the American stretches of the Circum-Pacific belt. Together with the Commander Islands and the related trench, it stretches 2 000 kilometers and is bordered by the Bering abyssal plain on the north. In the east, it ends with the fold area of the southern coast of Alaska, which is underlain by sedimentary and volcanic rocks of Cretaceous and Paleogene age intruded by granites. Here, geosynclinal troughs were initiated in the oceanic crust in the Cretaceous, as on the Kamchatka, and developed through the Paleogene into the Neogene when the included rocks were folded.

The southeastward continuation of this area is, after a break, the fold area of the Coast Ranges in Washington, Oregon, and California. It has also resulted from the accumulation of thick Cretaceous and Paleogene greywacke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sandstone, siliceous shale, and spilite in troughs in the oceanic crust and experienced repeated folding between Neogene and Quaternary times.

To the south there exists the large isolated fold area of Central America. It looks like a huge arc which extends from Central America (Mexico, Guatemala, and Honduras) eastward across Cuba and the Greater Antilles, then turns southward across the Lesser Antilles, and runs westward across the Coast Ranges of Venezuela into the Andes of Columbia and Equador (Fig. 30).

This arc is an example of the mature fold areas of Columbia and Venezuela, as well as of Mexico and Cuba, passing along the trend directly into the typical island arc of the Lesser Antilles where the geosynclinal cycle is still going on. The arc rims the deep Caribbean Sea basin and, in turn, is rimmed by the Puerto Rico Trench as deep as 8 kilometers.

The tectonic cycle of the Columbian Andes began with the initiation of geosynclinal troughs as far back as early in the Paleozoic, continued through the Mesozoic and came to a close in the Neogene. To the east, in the Venezuelan Andes, the base of the sequence consists of the Sebastopolo metamorphics of Mesozoic age. Here, troughs began to subside as late as Mesozoic time and continued their development till the middle of Neogene time. The Antilles arc has evolved on the crust since Cenozoic (Eocene) time. On large islands—Cuba, Haiti, and Puerto Rico—folding was terminated in Eocene-Oligocene times. It was characterized by major thrusting and wrench faulting, and as a result, deep-seated ultrabasic rocks, gabbros, and now metamorphosed basalts were brought to the surface. According to A.L. Knipper, these make up large slices of the ocean floor (the basaltic layer of the oceanic crust) displaced on thrust planes. This suggests that the area began to evolve on the ocean floor.

The other deep of the ocean floor, known as the Cayman Trench, separates Cuba from Haiti and Jamaica. It is a long, narrow and deep (down to 7 000 meters) depression collinear with a number of faults farther to the west cutting across Central America within Guatemala. This is one of the largest fault systems in America.

The last, Cenozoic area of the Circum-Pacific belt comprises the Chilean end of the South American Andes and the arc of the submarine highs and islands of South Georgia, South Sandwich and Scott. This arc has much in common with the Antilles arc.

Within the Andes of South Chile and Tierra del Fuego, the geosynclinal cycle began in the Early Paleozoic and continued through the Paleozoic and

Fig. 30. Diagrammatic map showing major tectonic elements of Central America:

1 — ancient platforms;
2 — outcrops of basement of young platforms;
3 — sediment-covered areas of young platforms;
4 — fold area of West Coast of Mexico;
5 — Cenozoic volcanic belt of Central Mexico;
6 — Neogene fold areas;
7 — long-developing geosynclinal fold system of Andes of Columbia and Venezuela;
8 — intermontane and marginal basins of orogenic stage;
9 — major anticlines;
10 — deep-sea trenches;
11 — swells on ocean floor;
12 — major anticlinorium;
13 — deep-seated fault;
14 — graben;
15 — outcrop of ophiolite complex;
16 — major volcanoes;
17 — floor of deeps of Caribbean Sea and oceans

Mesozoic into the Cenozoic. Folding took place quite recently, in Neogene time. The arc of the South Sandwich Islands is the direct extension of the Andes, although it is in a much earlier stage of development. Its continuation is the Antarctic Peninsula whose geosynclinal cycle was completed rather long ago.

Clearly, a succession of fold areas has formed within the Circum-Pacific belt, their ages becoming younger in an inward direction. The youngest Cenozoic fold areas have now consolidated only in a few places. Their vast regions, including systems of island arcs and the adjoining ocean deeps, are in a rather early stage and can be considered today's geosynclinal areas of the Circum-Pacific belt.

FORMATION OF GRANITIC AND METAMORPHIC ROCKS OF THE BASEMENT WITHIN FOLD BELTS

Studies of the present island arcs on the margins of the Pacific Ocean help explain and properly evaluate the intricacies of the early life of geosynclinal areas initiated in the oceanic crust. It has been found that metamorphic rocks, particularly gneisses invaded by granites, are exposed in many places on some uplifts within island arcs and on large related islands and peninsulas.

Exposures of such rock types are known from Kamchatka, Taiwan, the Philippine Islands, Cuba, and many other regions. These are for the most part crystalline schists and gneisses (plagiogneisses) composing isolated massifs. The massifs were earlier regarded as the ancient metamorphic basement of Paleozoic or even Precambrian fold areas. According to radiometric dating, these are very young metamorphic rocks of Mesozoic, often Cretaceous, or even Paleogene age.

Therefore, in some places the sediments, as well as lavas and tuffs, which were deposited on the sea bottom in island arc areas, underwent strong metamorphism in the Cretaceous and Paleogene.

Metamorphic rocks, and also granites, are much denser than sedimentary rocks; hence, they are detected at depth mainly by seismic and gravimetric techniques. The metamorphics have been found in many regions beneath the sedimentary and volcanic series of island arcs and thus play a major role in the structure of these young highs.

Not only volcanic materials, but also hot escapes may have broken from below through deep-seated faults to replace and metamorphose, in some places even granitize, the sedimentary and volcanic rocks within uplifted areas of the island arcs and along these faults.

Thus relatively small massifs, embryos, as it were, of the crustal granitic-metamorphic layer, formed at depth. As the island arcs slowly developed, the volume of granitic and metamorphic rocks increased.

The massifs of granitic and metamorphic rocks are enormous on large islands and peninsulas, such as the Kamchatka Peninsula, the Japanese Islands, the Philippines, New Guinea, and Sumatra. Many scientists (M. S. Mar-

kov, Yu.M. Pushcharovsky, and others) correctly argue that these islands represent a subsequent phase in the evolution of island arcs.

Formidable ridges then rose, with the granitic-metamorphic layer at their base. Thick piles of sedimentaries and volcanics have accumulated in narrow intervening basins and can provide materials for further conversion into the granitic-metamorphic layer. The area of large islands of Indonesia (such as Sumatra and Java) is precisely in this stage.

The process similar to that observed in island arcs, that is, characteristic of the early stage of granitic-metamorphic build-up, took place in ancient times within major fold belts, when the geosynclinal areas were underlain by the oceanic crust. The granitic-metamorphic layer had occupied vast areas by the end of the Riphean and was fairly thick and stable. As time passed, it underlied the other type of geosynclinal troughs, formed by breaking-up and pushing-aside of blocks of the continental crust.

In the second half of the Riphean, when the Caledonian systems of geosynclinal troughs were initiated, the would-be fold belts still included vast areas of the oceanic crust; hence, many geosynclinal troughs were underlain by this type of crust. However, large massifs of the granitic-metamorphic basement existed at that time, and some systems of troughs were derived from the rupture of this basement.

After the Baikalian folding epoch, even more extensive areas underlain by the granitic-metamorphic layer originated within the belts, and minor belts were totally transformed into young platforms.

The Hercynian systems of geosynclinal troughs were initiated in the pre-Paleozoic continental granite-gneiss crust produced in the middle or at the end of the Riphean. To form these systems, the crust was pushed aside along deep-seated faults, and the shattered basaltic layer and some ultrabasic rocks of the upper mantle protruded into the bottoms of the troughs. That is why ophiolite underlies the geosynclinal columns. Alternatively, the Hercynian systems of geosynclinal troughs may have been initiated in remnants of the previously vast sections of the oceanic crust.

The Alpine fold area provides an example of three geocynclinal cycles in the Mediterranean belt of Eurasia.

At the time of the first, Baikalian cycle, geosynclinal systems developed in an oceanic crust during the late Proterozoic.

During the second, Paleozoic (Hercynian) cycle, geosynclinal troughs and even their systems were generated in a thin consolidated continental crust composed of metamorphic rocks. The cycle began in the Ordovician-Silurian and ended with the Hercynian folding late in the Paleozoic.

The third cycle was restricted to the central part of the Mediterranean belt (Alpine fold area). It lasted from the Triassic and Jurassic, when geosynclinal systems trending in the same direction as the Hercynian ones began to evolve, through the Neogene.

As a result, the continental crust (granitic-metamorphic layer) beneath the Mediterranean belt became, on the whole, very thick. It is especially thick under mountain ranges, such as the Pamirs, Greater Caucasus, and Alps, where its thickness is 60 kilometers. But beneath median masses such as the Pannonia mass, which is now the basement of the Hungarian Lowland, the granitic-metamorphic layer is only 25 kilometers thick. It apparently

consolidated during the first cycle, the Baikalian folding epoch, and has not thickened since.

At the outset of the geosynclinal cycle on the oceanic crust, a relatively thin granitic-metamorphic layer appears to form. The repeated subsidence of geosynclinal troughs, say, Paleozoic in the late Proterozoic (Baikalian) continental crust and Mesozoic-Cenozoic (Alpine) in the Baikalian or Paleozoic continental crust, further thickened the granitic-metamorphic layer beneath the fold belts.

Because the Circum-Pacific belt occupies the periphery of the huge Pacific Ocean floor, we can observe the successive inward shift of the geosynclinal cycles rather than the sequence of geosynclinal cycles in a particular area. The result is also the gradual build-up of the granitic-metamorphic layer.

VII

EVOLUTION OF ANCIENT AND YOUNG PLATFORMS

BASIC STAGES

Ancient, and young platforms both passed through two stages in their evolution. First, their basement formed; second, this basement was overlain by a structurally different thick sedimentary cover.

Ancient platforms have existed as continental blocks since mid-Archean time (nearly 3 000 million years ago). Their geosynclinal cycle continued, with slight differences for different platforms, till the middle or end of the Proterozoic (1 800-1 650 million years ago). During Riphean time (late Proterozoic, 1 600 million years ago), a sedimentary cover of the ancient platforms began to accumulate, that is, their basement had consolidated by that time.

The basement of young platforms began to form within fold belts much later (in mid-Proterozoic time); some of its regions attained stability at the beginning, others, at the end of the Paleozoic.

The geosynclinal cycle results in the formation of the granitic-metamorphic layer of the earth's crust. Then the continental crust thus produced is deformed to generate the various platform-type structures.

The platform-type crust is essentially the true continental crust. Platforms make up the great bulk of all continents while the present geosynclinal areas, only a small fraction.

The basement of ancient platforms consolidated mainly after the Karelian and Hudsonian folding epochs early in the middle Proterozoic (2 000-1 800 million years ago). By that time, early Proterozoic geosynclinal cycles had come to an end within the fold areas, and the Archean massifs had been granitized once more. A protosedimentary cover and the related intrusion complexes were widespread within the platforms. Some regions, mainly on the margins of platforms, experienced even more recent granitization and metamorphism. Here, acid volcanic outpourings can be observed in some places such as the porphyries of Kiruna and Öland on the Swedish seg-

ment of the Baltic shield. Therefore, we can now say that by that time the earth's crust had consolidated and become a platform.

However, the basement of ancient platforms was not yet overlain by a genuine sedimentary cover that would blanket the various surface features of the basement. The sedimentary cover is invariably associated with vast lowered areas, which contain depressions and bulges of the basement, but are, on the whole, lower than shields, highly elevated parts of platforms.

While some sections of platforms were rising to become shields and others were subsiding to become sediment-covered areas, a continuous sedimentary cover and platform-type structures originated. Consequently, we can outline two basic phases in the evolution of ancient platforms: the early phase, in which the basement is uplifted as an entity, and the main phase, characterized by differentiation of platforms into shields and vast sediment-covered areas.

Most of the ancient platforms—the East European, Siberian, North American, North African, South African, Australian, China-Korean, Tarim, and others—had their basement consolidated late in the middle Proterozoic-early in the late Proterozoic and since then have been the most stable sections of the continental crust.

The earth's crust beneath ancient platforms contains the thick granitic-metamorphic layer, is immobile, unlike geosynclinal areas, and undergoes mainly vertical uplift or subsidence related to major faults. The vertical movements can be seen as rapid subsidence on fault planes to produce grabens and aulacogens, or protracted intermittent sinking or uplift of extensive shields and sediment-covered areas, basins, and anteclises.

Early in the life of a platform, when it was not yet overlain by a continuous sedimentary cover, large grabens, trenches, as it were, and aulacogens originated. In some of them, within the fault-bounded troughs, not only sedimentary series accumulated, but also basic volcanics, and they were folded at places and invaded by small basic and occasionally alkalic intrusions. More or less complex fold structures are often found in aulacogens. Perhaps all of them are extremely local dislocations related to a graben or to part of it.

Some aulacogens reach hundreds and thousands of kilometers in length and dozens of kilometers in width. These are the Pripyat-Dnieper-Donets, which includes the Donets Basin, and Pachelm on the East European platform; the Vilyui on the Siberian platform; the Amazon in South America (so far little studied), Wichita on the margin of the North American platform (in Oklahoma and Texas), and others. Some of the aulacogens subsided during many geologic periods, while others in a relatively short time and then were overlain by a thick sedimentary cover. On the whole, however, they are restricted to the early phase in the evolution of a platform. Some of them further developed for a long time. For example, the rocks within the Donets Basin were folded late in the Paleozoic (Permian), whereas the Pripyat-Donets aulacogen was initiated in the East European platform in the middle of Riphean time.

The structure and history of aulacogens have much in common with geosynclinal troughs, but they began to develop in the basement of ancient platforms and are not intruded by truly granitic rocks.

The main phase of platform development is incomparably longer and includes the subsidence of large sections of platforms and the formation of sediment-covered areas of platforms. Different sections subsided at different times and different rates to produce more or less extensive flat depressions separated by elevated areas. In the depressions, sedimentary sequences, sometimes very thick, slowly accumulated; in the higher areas, there occurred breaks in sedimentation (see Fig. 8).

The sedimentary cover of the most ancient platforms had formed by the middle or the end of the Riphean. From then on, typical platform-type depressions and elevations began to form. Three types of depressions can be singled out by shape and partially by mode of formation: marginal basins, syneclises, and amphiclises.

A marginal basin is a broad depression elongated along the periphery of the platform. It is an asymmetrically bent margin of the platform, steep at its end and becoming gentler inward. Marginal basins were first recognized on the Siberian platform by E.V. Pavlovsky, who called them pericratonic, that is, situated on the margin of a craton, an ancient platform. Many of them evolved for a very long time. For example, some of the marginal basins of the East European platform subsided from the middle of the Riphean to the Mesozoic, whereas others are sinking even now (Near-Caspian basin). That is why some of them are filled with thick piles of sedimentary rocks (the sedimentary sequence of the Near-Caspian basin is nearly 20 kilometers thick).

A syneclise is a flat, round, oval, or elongate depression, the most concave in the centre and becoming more gentle outward. It is produced by slow downwarp of a region of a platform. The time interval of downwarp is somewhat different for different syneclises; it generally stretches across part of Paleozoic time and Mesozoic time, or across only Mesozoic and Cenozoic times.

Amphiclises have been acknowledged only recently. These are basins in the shape of a giant amphitheatre with a fairly flat bottom and steep flanks. Amphiclises are characteristically bound or cross cut by faults and filled with enormous masses of lavas, tuffs and other volcanic materials, brought to the surface through faults and forming thick piles in some places. The Tunguska amphiclise on the Siberian platform is the most typical example.

Between these depressions lie gentle uplifts—arches and anteclises, somewhat larger structures—which are thought to have remained after the depressions subsided. Downwarp is the leading process in the evolution of platform-type structures.

The basement of young platforms is known to be made up of fold areas of different ages constituting fold belts. This basement also contains isolated massifs of early Proterozoic granitized rocks. More common are massifs generated in the middle of the Riphean by the local Kibarian, Isidonian, and Espinasian epochs of folding, granitization, and metamorphism whose age is about 1 000-1 300 million years. The Baikalian folding was even more extensive and produced the Timan-Pechorian area northeast of the East European platform and the Baikalides of the Baikalian Highlands, Yenisei Ridge, and Taimyr, Siberia. The Baikalides also make up most of the minor Intra-African and Brazilian fold belts which consolidated at the end of the Proterozoic. Then a sedimentary cover began to form within these belts,

that is, they started to evolve as platforms. The major fold belts include many Caledonian fold areas that changed into the basement in the middle of the Paleozoic (between the Silurian and early in, or the middle of, the Devonian).

In the major fold belts, these Kibarian, Baikalian, and Caledonian fold massifs were largely overlain by the sedimentary cover. It was metamorphosed and invaded by various intrusions in some areas. The sedimentary cover of median masses has much in common with that of ancient platforms, but is of local extent. It has undergone local folding and metamorphism and is even invaded by granites in some regions. However, it was not yet a real sedimentary cover of a platform.

Within the major fold belts, only at the end of the Hercynian geosynclinal cycle did broad sediment-covered areas of the platforms begin to downbuckle and a true sedimentary cover to accumulate on the surface of the Baikalian and older massifs and the Caledonian and Hercynian fold areas. It is of Mesozoic and Cenozoic age and fills vast platform-type depressions. The sedimentary cover is epi-Hercynian, because it was laid down after the Hercynian folding and rests on the Hercynian and all the older parts of basement of the fold belts.

The epi-Hercynian cover blankets huge areas of young platforms: the Turanian, West Siberian, and Dunbeian sediment-covered areas of the Ural-Mongolia fold belt, and others. Since its formation, large parts of fold belts have changed into typical platforms. The same two stages can be recognized in their history, as on ancient platforms.

The first stage involves the formation of grabenlike depressions, some of them very long and deep, along the faults cutting through the basement. On all platforms, some of these depressions are disturbed by folds and contain volcanic series and small igneous intrusions. Being of epi-Hercynian age, they are generally filled with Triassic and Jurassic series, often thick, containing such volcanic rocks as andesite, basalt, and tuff. Unlike the aulacogens of ancient platforms, scientists have suggested calling these depressions taphrogenes (Sobolevskaya, 1965).

The second, longer stage in the history of young platforms is characterized by generation of gentle uplifts, similar to shields, and by extensive and long-developing depressions looking like syneclises and pericratonic downwarps of ancient platforms. On many young platforms, the depressions were initiated in the Jurassic and then developed during the Cretaceous, Paleogene, and Neogene; some of them are subsiding at present.

THE ORIGIN OF PLATFORM-TYPE DEPRESSIONS

It is highly probable that the depressions of all platfoms are of the same origin.

N.S. Shatsky was the first to ask why platform-type depressions downwarp (1947). He believed that the processes beneath the earth's crust must be responsible for this, but whether the flowing away or compaction of subcrust-

al material caused downwarp was unclear. In attacking the problem, he was inclined to the latter alternative. Syneclise origin was also considered by V.A. Magnitsky, V.V. Beloussov, E.N. Lyustikh, and many others. In recent years, the causes of downwarps and uplifts of the earth's crust beneath the platforms and geosynclinal areas have been more specifically studied by S.I. Subbotin and his assistants (G.L. Naumchik and I.Sh. Rakhimova). They used geophysical information on the earth's crust and on the heterogeneity of the upper mantle, as well as theoretical and experimental data on the mantle material. These scientists have concluded that the main cause of uplift and subsidence of the earth's crust within platform-type depressions are compaction and softening of the material that make up the upper mantle. These processes operate at depths approximately between 50 and 300 or 400 kilometers and involve mantle material transformation into a denser state following changes in thermodynamic conditions.

Experimental results obtained by many scientists and theoretical calculations for systems of minerals of the basic rocks constituting the upper mantle, indicate that definite thermodynamic conditions determine their own mineral associations. Changes in temperature and pressure will cause the minerals to alter. The most important process responsible for the compaction of the mantle material may be the conversion of spinel peridotite composing the upper mantle into garnet peridotite. The latter is denser; hence, the volume of the mantle material is reduced greatly. As a result, the upper part of the mantle and the earth's crust that lies above the zone of compaction subside to produce a gentle downwarp on the surface of the crust. These very slow processes may lead to the formation of major types of depressions of platforms during several geologic periods.

This suggestion is supported not only by theory, but also by data on the composition of xenoliths in kimberlites, which were expelled from the mantle to be found in the diamondiferous pipes of Siberia and South Africa. They consist precisely of spinel and garnet peridotites and eclogite.

The compaction of material in the lower crust may be due to the transformation of basaltic rocks into eclogite (pyroxene-garnet rock), which is of the same composition, but much denser.

The appearance of platform-type depressions and the contained sediments implies that the respective parts of fold belts have become platforms. Since then areas of ancient and young platforms have combined to produce vast expanses of continents. Platforms—the most typical structural units of the continental crust—have occupied most of the continents since the end of Paleozoic time.

Figure 9 shows the distribution of continental platforms and Cenozoic geosynclinal areas some parts of which are modern geosynclines.

As to the areas with the Mesozoic basement, none of them is overlain by a true sedimentary cover; hence, none of them is a true platform (craton). Perhaps their present state is similar to that of young platforms early in the Paleozoic or of ancient platforms in the middle Proterozoic, before the Riphean. In other words, these areas are in an early stage of their evolution as platforms, with no continuous sedimentary cover present.

PRINCIPAL VALUABLE MINERALS OF THE SEDIMENTARY COVER OF PLATFORMS

Oil and gas fields and deposits of other valuable minerals have been discovered in the sedimentary cover of platforms. Many of them are of the same age as sediments that piled up on the sea bottom, others accumulated on the surface of continents, and still others are related to volcanism. Combustibles, above all oil and gas, are the most important among these valuable minerals. The largest petroleum deposits in the world, including the giant fields recently discovered within the West Siberian Lowland, occur in the sedimentary cover of ancient and especially of young platforms. Prolific oil and gas fields have been discovered on the eastern Russian, Turanian, and West Siberian sediment-covered platforms, in North Africa, on the Arabian Peninsula in the Persian Gulf area, in the southern United States, on the North Alaska sediment-covered platform, and in other areas. Sediments of platforms enclose deposits of fossil coal which form exceedingly large coal basins, although these are not so rich as those in the foredeeps of geosynclinal fold areas. Finally, the deepest depressions of platforms contain deposits of rock, potassium, and magnesium salts.

Sedimentary series of platforms, in particular those of depressions, are the richest sources of fresh and mineral waters. Many large cities and industrial centers, in particular Moscow, are largely or solely supplied with subsurface waters which are generally of a very high quality. Many mineral waters and brines are recovered also from the sedimentary cover of platforms.

Placers of gold and some other metals are also found in the sedimentary cover of ancient platforms. Moreover, numerous kinds of clay, sand, limestone, chalk, dolomite, and other rocks used by building industry, and sedimentary iron ores, bauxite, sulfur, and many other minerals are extracted here.

The igneous activity on platforms also gives rise to many valuable minerals. Thus copper and copper-nickel ores, and in some areas iron ores are related to traps and associated intrusives. Explosion pipes filled with kimberlite, an ultrabasic rock known from the Siberian and South African platforms, contain deposits of diamond which were introduced into these pipes from the deep interior of the mantle.

To summarize, many valuable deposits of different kinds of mineral materials required for building and other industries owe their origin to the sedimentary cover of platforms.

VOLCANIC BELTS AND EPIPLATFORM OROGENESIS

Along with the formation of platform-type structures, the earth's crust develops within platforms so that volcanic belts are originated from epiplatform orogenesis and similar processes of rifting.

Volcanic belts and zones are extensive strips of the earth's surface where the crust was cut by numerous faults which were channelways for the rise

to the surface of volcanic materials to form thick piles of lavas, ashes, tuffs, and others. The volcanic belts are not associated with the geosynclinal cycle, but postdate it, occurring early in the development of a platform. They appeared before the deposition of the sedimentary cover, namely, during the uplift of the young fold area and the formation of a mountain area. The Mesozoic volcanic belt that encircles the Pacific Ocean is the most typical example. Here, numerous faults cut through the earth's crust late in Early Cretaceous time along the young fold areas of Kamchatka and Sikhote-Alin and the Okhotsk-Chukot area; the Nevada area and that of the Coast Ranges, North America; and in Mexico and the Andes. Magma rose to the surface through these faults, and volcanoes appeared and erupted enormous amounts of lavas and other materials (ashes, tuffs, and others) till the end of the Cretaceous. A long, albeit discontinuous, belt of Cretaceous volcanoes emerged along the Pacific coasts of Asia and America.

Similar volcanic belts are also known on the surface of fold areas within major fold belts (late Paleozoic belt of Kazakhstan) and on ancient platforms (volcanic area of Kiruna, Sweden, of middle Proterozoic age).

A.L. Yanshin has coined the term epiplatform orogenesis for the mountain-building processes on platforms. Epiplatform mountain building involves for the most part some areas of young platforms. The best known areas of epiplatform orogenesis are those of Tien Shan, Altai, Mongolian Altai, Eastern and Western Sayan Mountains, Kuznetsk Alatau, Kunlun Shan, Nan Shan, and Central Asia, where systems of great mountain ranges have been recently uplifted and separated by deep depressions. In mountain ranges, many peaks and ridges attain 3 000-4 000 meters or even 4 500 meters (Belukha in the Altai) and 7 000 meters (Khan-Tengri in the eastern Tien Shan) in height. The growing mountain ranges were, of course, dissected by rivers and eventually worn down, with the transportation of debris by streams onto plains or adjacent basins. These subsided while the mountain ranges were rising and thus in that period were filled with exceedingly thick piles of sediments derived from the rocks that made up the ranges. Examples of the basins formed between ridges are the Fergana, Issyk-Kul, Chu, and Ili in Soviet Central Asia, Zaisan in the Altai, and Dzhungar. The starting time of this process is judged by the age of the relevant rocks.

In Central Asia, including the Soviet part, the epiplatform orogenesis began late in the Paleogene-early in the Neogene and is still going on. Its age is the same in the Verkhoyansk-Chukot area and Siberia; the Appalachian Mountains, North America; Atlas, North Africa; East Australia; and other areas.

While some of the massifs were rising or sinking during epiplatform mountain building, some of the sedimentary series were crumpled into more or less complex folds. Also, some of the members of sedimentary rocks were shoved against each other for short distances. Folds were occasionally formed by the slipping of sedimentary series on the inclined underlying surface. The result may also have been the formation of rather complex fold structures.

Epiplatform orogenesis manifested itself also in some regions of ancient platforms, where young mountain ranges rose, but to a much lesser extent than in the above-described regions. Thus was formed the Eastern and Western

Ghats, India; the Ahaggar and Tibesti Mountains, Africa (with heights up to 3 400 meters); the Guiana Highlands, South America; the Middle-Siberian Highlands, Siberian platform (up to 1 700 meters high); the Rocky Mountains of Colorado, North America; and others.

A specific kind of epiplatform orogenesis is rifting, which is the formation of a system of long and deep trenches or grabens along great faults with a deep collapse of the earth's surface. Rifting is generally accompanied by uplift of rift flanks to produce high uplands. Only three true rift systems are known on continents. The first is the above-mentioned system of the Great African Faults which extends in a north-south direction throughout all of Africa for 6 000 kilometers. Its most imposing graben—the Red Sea—has fallen so deeply, and its sides have been pushed aside so greatly that not only the basaltic layer but even in some cases the mantle possibly protrudes directly into its bottom. The grabens of the lakes of Tanganyika, Nyasa, and Rudolf belong to the same system. These are associated with faults along which numerous volcanoes are located.

The second system comprises the Rhine Graben in Western Europe and its northern continuation, the Oslo Graben, Norway. It is much less imposing, though volcanism is associated with it. A number of extinct volcanoes occur along its faults.

The third system includes several grabens in the Stanovoy Range area and Baikal Mountains, Siberia. Here, three largest grabens merged and were filled with water to form Lake Baikal, the deepest lake in the world (1 620 meters deep). The shallower Barguzin, Upper Angara, Muy, and Upper Chara depressions are on their continuation or nearby. Small extinct basaltic volcanoes (Obruchev and Mushketov in the upper reaches of the Vitim River, in the Tunkin depression) are related to the faults that bound these depressions.

Uplifts of extensive, generally elongate sections of platforms of different ages is probably caused by the processes operating deep inside the earth's crust or in the mantle. These appear to be the result of the material becoming less dense along deep-seated fault-zones extending into the mantle and serving as passageways for heat flow which changes the physical properties and composition of metamorphic rock complexes.

VALUABLE MINERALS IN THE ACTIVATED AREAS OF PLATFORMS

Until recently it has been commonly thought that the metal wealth of the earth's interior is restricted solely to fold areas. But we now know that considerable importance should be attached to the metalliferous deposits associated with the parts of platforms that were somehow activated, that is, with those that were disturbed by fault-zones exhibiting young extrusive and intrusive igneous activity.

Areas of young volcanism in activation zones not infrequently contain various occurrences and deposits of such metals as gold, silver, lead, zinc, copper, mercury (cinnabar), and many others.

The most typical activated area on the ancient platform is the Rockies of Colorado, the southwestern North American platform. These are a system of mountains made up of upfaulted blocks of sediment-covered basement of the ancient platform. The mountains rose late in the Cretaceous-early in the Paleogene, during the Laramian folding. The movements were accompanied by pronounced igneous activity during which small intrusions, in particular laccoliths, were emplaced, volcanoes formed, and volcanics accumulated. An elongated zone of dikes and stocks of diorite, granite-porphyry, quartz-monzonite, and other rocks, runs northeastward along faults and intersects obliquely the Colorado Mountains. The well-known deposits of gold, silver, tungsten, as well as those of copper, zinc, molybdenum, uranium, and other metals are associated with this zone, called the mining zone.

Metalliferous occurrences and deposits are more common in the areas of epiplatform orogenesis on young platforms than in those on ancient platforms. In some places they are related to igneous bodies, while in others igneous rocks do not crop out, but may occur at depth. For example, in Tien Shan, which underwent epiplatform orogenesis after Paleogene time, vein occurrences are known of lead-zinc and cinnabar, as well as barite and fluorite of Neogene age.

In the Altai, the mercury mineralization can probably be assigned to epiplatform orogenesis. However, no igneous activity of this age is known so far.

Many scientists believe that the fluorite-barite veins with galena and sphalerite, and the quartz-fluorite-barite veins with silver in the Ore Mountains, near Freiberg, GDR, are of Paleogene-Neogene age and associated with orogenesis (A.D. Shcheglov, 1971). The same age has been proved for the metalliferous occurrences in the French Massif Central of Paleozoic age. Barite veins containing fluorite and lead-zinc sulfides are known from a system of young faults forming the Rhine graben.

Many metalliferous occurrences are also related to volcanic belts and the associated intrusions. Thus gold occurs in the Okhotsk-Chukot volcanic belt.

Therefore, activated areas of ancient and young platforms, including volcanic belts, deserve attention and diligent investigation aimed at discovering valuable minerals.

VIII

THE TOPOGRAPHY AND TECTONICS OF THE OCEAN FLOOR

PRINCIPAL TOPOGRAPHIC FEATURES AND THE PHYSIOGRAPHY

Until the turn of the century ocean basins were regarded as merely the sections of the continuous earth's crust that later subsided between the continents. However, data on the vegetative and animal realm of different continents indicate the common origin of, and affinities between, many groups of plants and animals in different parts of the world. This has led to the hypothesis that strips of land once existed across the space now occupied by oceans and served as paths along which animals and plants were distributed over the continents.

M.A. Menzbir, the prominent Russian zoologist, believed that the continent of Pacifida had existed in the area of the present Pacific. E. Suess, an Austrian geologist, produced evidence for the existence of a continent that once linked Africa, South America, Hindustan, and Australia together, and named it Gondwana. Many outstanding scientists (E. Haug, A.D. Arkhangel'sky, and others) suggested that extensive ancient platforms were covered by ocean water and that elsewhere continental fold belts and mountain chains continued onto the ocean floor.

With the progress of gravimetry, gravity was found to be positive within oceans and negative within continental mountain areas. This prompted geophysicists to favor the concept of the fundamental differences between the continental and oceanic crust. One of the first to substantiate this concept and elaborate the isostasy theory, according to which blocks of the continental and oceanic crust are in a state of balance, was the Russian geophysicist I. D. Lukashevich.

In recent years, the earth's crust has been explored by geophysical methods. In particular, the seismic waves induced by earthquakes or by artificial explosions have been recorded and interpreted. As a result, three principal layers have been found to compose the earth's crust: the sedimentary, granitic

(most typical constituent of the continental crust which is almost missing beneath the oceans), and basaltic (ubiquitous).

The continental slope has been found to play a special part in the topography of the ocean floor. It was earlier considered a simple, though major, feature, which separates continents, "the highest mountains on the earth's surface" (M.V. Lomonosov), from flat ocean basins. Indeed, being a ledge representing the main transition between continental and oceanic depths, the continental slope is everywhere clear cut. The granitic layer thins out beneath the continental slope or in some places immediately beyond its limits, beneath the ocean floor. The continental slope is, therefore, the main structural boundary between the continental and oceanic crust.

Geologically, we shall assign to the ocean floor the area fringed by the continental slope, rather than the earth's surface covered by oceans. Shallow-sea regions, shelves, and extensive shelf seas (North, Barents, Kara, East Siberian, Chukchi, Yellow, South China, and others) are sea-covered margins of continents underlain by the continent-type crust. These are separated from the actual ocean floor by the continental terrace. It is no wonder that these shallow seas are now objects of intense search and prospecting for oil and gas (shelf off North Alaska, North Sea, and others). The structures of the earth's crust that are observed on the coasts of continents continue into these regions. Consequently, the shelf sea may be underlain by oil-, gas,- or coal-bearing series, as well as other mineral-bearing series known on the adjoining land.

Beyond the continental slope, within the deep ocean floor, all signs of continental structures disappear. For example, quite distinct fold areas approach the Altantic coastlines of England, Ireland, France, and Spain. These are the Caledonides of Great Britain; parts of the Hercynian fold area of the Armoric Peninsula, France; and the Alpine and Hercynian fold areas of North Africa (Algeria and Morocco). All of them are cut off by the coastline, but extend beneath the ocean floor in the strip of the shallow-sea continental shelf. However, these structures have no counterparts whatsoever within and beyond the continental slope. They are not expressed in the topography of the ocean floor, where we might expect stumps of ridges elongated along the trend of submerged fold structures, nor have geophysicists found them beneath the ocean floor. The situation is the same off the eastern United States, Canada, and other regions. In no way do continental structures manifest themselves on the ocean basin floors. Any trace of continental structures disappears together with the granitic layer of the earth's crust.

Studies of the physiography of the ocean floor recently undertaken by the research ships of the USSR Academy of Sciences and expeditions of the United States and other countries have shown that the surface of the ocean floor is very complex. It has been found that certain topographical features are related to the crustal thickness and structure and the thickness of bottom sediments. Some of these features are associated with volcanism, others with greater, sometimes considerable seismicity.

Thus, we can speak not only of the surface features of the sea and ocean floor, but also of their relationship to the interior of the earth's crust. Also, we can delimit the tectonic elements on the ocean floor, though some of them are obscure.

Ocean-floor features are recognized rather distinctly by the totality of topographic characters and by geophysical evidence. Many scientists have recently singled out and described types of the topographic features and tectonic elements of the ocean floor.

Abyssal (deep-water) plains are the broadest features of the ocean floor. These flat areas occur at depths between 4 000 and 6 000 meters, are separated by submarine swells, and are bordered on the landward side by the continentotal rise.

Two kinds of flat areas can be observed on the ocean floor. Some are very extensive underwater plains occurring only in the Pacific. Others, which occupy the bottoms of large submarine basins, are much less extensive, though still broad, expanses of the flat floor rimmed by swells. Such basins are major features of all ocean floors.

Near the continental slope many submarine plains and basins are aproned by thicker bottom sediments. These are extremely thick near deltas of large rivers discharging great volumes of sediments into the ocean. As a result, the surface of many plains becomes inclined at the foot of the continental slope. Some abyssal plains are undulating or even rugged; they are covered by sediments only within isolated patches, while lava flows project from under them in higher areas. Tectonically, submarine plains and basins are stable, undisturbed areas of the ocean floor.

Abyssal plains co-exist with elevated "marginal plateaus", described by V.V. Beloussov (1968) and other scientists. These are flat or slightly inclined areas of the floor much elevated above abyssal plains and bounded by scarps. At the same time, they differ from shelves in greater depths (1 000 to 2 000 meters) below sea level, as if they are really a kind of submarine plateau. Examples are the Blake Plateau off the Atlantic coast of North America and the plateaus south of Rio de Janeiro, east of the Falkland Islands, west of the Guinean and Angolan coasts, south-east of New Zealand, and off the California coast. It should be mentioned that some of them, such as the Blake Plateau, are underlain by a continental crust containing a thin granitic-metamorphic layer. These plateaus appear to be parts of the lowered shelf.

Totally different from submarine plains and basins are oceanic trenches, narrow and very long depressions running for hundreds and thousands of kilometers and reaching depths of 10 000 and even 11 000 meters below sea level. These trenches are mainly on the periphery of the Pacific floor, almost completely encircling it.

Submarine swells on the ocean floor include mid-oceanic ridges and various arches and block-faulted uplands.

The mid-oceanic ridges are of quite specific structure and are the basic features of oceanic topography. They are significantly active in terms of present-day volcanism and seismicity. Their complex structure has prompted many scientists to call them oceanic mobile belts. The ridges run the length of the Atlantic, Indian, and Pacific Oceans; the Mid-Atlantic Ridge, for example, runs exactly between the continents bordering the Atlantic Ocean. A mid-oceanic ridge is broad (up to 600 or even 1 000 kilometers) and its topography is extremely irregular. It consists of a number of longitudinal ranges. Its main feature is a crest within which occurs a rift valley and a high fractured plateau.

Volcanism is violent in mid-oceanic ridges and produces numerous seamounts. The ridges rise from 1 500 to 2 000 meters above the ocean floor, while some of their volcanic cones project from the sea. The highest ranges rim the rift valley. Also, within the mid-oceanic ridges the heat flow is greater.

While the heat flow from the ocean floor almost equals that from the continents and varies between 1.1×10^{-6} and 1.5×10^{-6} cal/cm$^2\cdot$s, being somewhat greater from areas of present-day volcanism, the heat flow from the mid-oceanic ridges is five to seven times greater, varying between 5.1×10^{-6} and 7.0×10^{-6} cal/cm$^2\cdot$s.

The mid-oceanic ridges are related in origin to systems of longitudinal faults cutting deeply into the mantle, and to numerous transform faults. These faults have broken the earth's crust into blocks standing differently, but most downfaulted within the rift valley. In 1965 great lumps, weighing up to 300 kilograms, were dragged out of the sides of the rift valley in the central part of the Indian Ocean and lifted aboard Research Ship *Vityaz*. These are composed of the ultrabasic rocks, peridotite and serpentinite, exposed at the sides of the rift valley. Consequently, mantle-derived ultrabasic rocks crop out in the rift valley of the Mid-Indian Ridge. Therefore, no crust is present in some areas of the mid-oceanic ridges. Isolated outcrops of ultrabasic rocks were also found in the Mid-Atlantic Ridge, particularly on St. Paul Island where these rocks form patches surrounded by volcanic rocks.

Patterns of magnetic reversals of varying magnitude are associated with the mid-oceanic ridges. Geophysical evidence suggests that the relevant magnetic bodies occur at shallow depths in the crust or the uppermost mantle.

All the mid-oceanic ridges constitute a single system crossing the ocean floors. It begins in the Arctic Ocean, runs along the axis of the Atlantic, then turns around the southern edge of Africa, and continues as the Western Mid-Indian Ridge. This ridge passes into the Central Mid-Indian Ridge which starts from the Gulf of Aden in the north and turns around Australia in the southeast. On passing into the southeastern part of the Pacific, it comprises a number of swells that cross the ocean obliquely to reach America near California. The total length of the entire system of mid-oceanic ridges is more than 60 000 kilometers. Other elevated features on the ocean floor are simpler and can be classified as archlike and block-faulted rises and marginal swells.

The archlike rises are gently sloped; some of them are thousands of kilometers long and hundreds of kilometers wide. Most of them, but not all, are crowned with volcanoes projecting out of the ocean and forming archipelagos composed of islands and atolls.

The block-faulted rises are clear cut, and because they rose on fault planes, many of them are tilted. More seldom are the rises having, according to geophysical evidence, the continent-type crust containing the granitic layer.

The marginal swells are known solely in the Pacific Ocean. They occur on the oceanic sides of the trenches that border the Pacific. The swells are long and asymmetrical, not high, but distinct on all the sides of the Pacific Ocean.

Scarps and steps, stretching, as in the Pacific, for many thousands of kilometers, are important features of the ocean floor. These are indicators of major faults along which the oceanic crust has been teared up and offset. In addition, numerous minor structures occur, such as scarps, isolated volcanoes,

gentle-sided hollows, small swells, and chains of volcanic cones forming ridges and manifesting the presence of faults.

Very interesting are the narrow submarine canyons, some arcuate and ramifying, that are mainly associated with the shelf and continental slope. Smaller number of them slope down on the ocean floor. Their origin is uncertain and debatable. Judging from their shapes, they are chiefly river valleys that were incised when the ocean stood lower and then sank and became covered by sea.

The above topographic and physiographic features of the ocean floor are distributed differently in different oceans. The distinction between continents and ocean basins lies not only in the crustal structure, but also in the tectonic elements and the topography whose origin is, of course, closely connected with the structure and history of the earth's interior beneath the oceans.

We still know little about the geology and tectonics of the ocean floor and are only gradually learning about them as a result of topographic and geophysical studies. But we can definitely say already now that certain similar topographic features of the ocean floor are of different structure and origin. On the other hand, different structural forms prevail in different oceans. The ocean floor is now an object of keen interest, because it is a probable source of many mineral materials, especially oil and gas.

The shelf parts of the floor are structurally the extension of continents. Hence they may be similar to the neighboring parts of coasts and thus contain the same minerals as on the continents. For example, oil is pumped from under the bottom of the North Sea shelf. American geologists believe that prolific oil fields occur within the shelf off northern Alaska. The bottoms of other shelf seas, especially in Northern Europe and South-East Asia, offer good prospects for petroleum. Moreover, continental shelves may prove to contain submerged placers of various valuable minerals and native metals.

Along with shelves, the abyssal floor should also be explored, especially the mid-oceanic ridges, where basic and ultrabasic (serpentinite) rocks are exposed at the ocean floor. These generally contain minerals of copper, manganese, nickel, chromium, and other elements, which may prove to be economically valuable under certain circumstances.

In the past few years, the geology of the ocean floor has attracted much more attention. Thus, many countries have embarked on geological and geophysical investigations of the continental shelves in searching for oil and gas.

PRINCIPAL TECTONIC FEATURES OF THE OCEAN FLOOR

Pacific Ocean

The Pacific floor makes up approximately half of the entire ocean floor; hence its diversity of topographic features and their origins. A number of special investigations into the tectonics of the Pacific floor have been carried out. The studies carried out by F.P. Shepard, T.F. Gaskell, D.G. Panov, H.W. Menard (1964), P.N. Kropotkin, and L.A. Shakhvorostov (1968) and younger fundamental works of V.V. Beloussov (1969), Yu.M. Pushcha-

rovsky (1971), G.B. Udintsev (1972), B.A. Sokolov, A.G. Gaynanov, D.V. Nesmeyanov, A.M. Sergeev, and A.P. Lisitsyn (1973) treat in sufficient detail all the evidence.

We shall now examine the basic tectonic features of the Pacific floor. This floor is known to differ considerably from the other ocean floors. Above all, the abyssal plains of the Pacific floor are very broad and more or less flat features lying at depths between 4 000 and 5 500 meters and even 6 000 meters. No such extensive and even areas of the ocean floor are present in other oceans (Fig. 31, insert on p. 144).

These almost undisturbed areas of the ocean floor are tectonically a specific type of structure of the earth's crust, sometimes termed thalassocratons. The earth's crust of the thalassocratons is only 5 to 8 kilometers thick.

The Pacific floor includes a number of extensive submarine plains and smaller basins. They are separated mainly by arches forming an elongate system, which is not yet a mid-oceanic ridge, exactly in the center of the ocean. It starts in the northwest as a submarine ridge (Emperor Seamounts) which is followed by the vast en echelon-arranged swell of the Hawaiian Islands.

East of the topographic highs lies the largest submarine East Pacific Plain bordered by the Aleutian Islands on the north, the North American coast on the east, and the mid-oceanic ridge on the southeast. The floor of the plain is the largest flat area on earth. It is only cut across by a series of parallel faults each 4 000 to 4 500 kilometers long. These are expressed on the ocean floor as scarps, block-faulted ridges, and rows of narrow depressions. All in all, nine traces of these faults are known (from north to south): the Mendocino, Pioneer, Murrey, Molokai, Clarion, Clipperton, Galapagos, Marquesas, and Sala y Gomez.

West of the system of the swells bordering the extensive East Pacific plain described above, three smaller plains are distinguished: the Western, Central, and Southern, and also several very small basins: the Melanesia, Caroline, East Mariana, and others. They are all separated by lines of islands and submarine uplands (Marshall, Gilbert, and Tokelau Islands, and others) and form in their entirety the floor of the southwestern and southern Pacific.

The East Pacific (mid-oceanic) Ridge, arcuate in outline, runs across the southeastern Pacific. It separates the Southern and Eastern Plains from several basins (from north to south): the Guatemala, Peru, Chile, and Belinshausen, which are off Central and South America and Antarctica and separated by elevated areas.

This ridge, composed of several swells, differs from the similar ridges of other oceans in the absence of a rift valley and in simpler topography. Nevertheless, it is characterized by seismicity, greater heat flow, and many volcanoes. One of the volcanoes that top this ridge is the famous Easter Island.

The Pacific floor includes a great number of arches crowned with volcanoes some of which constitute chains or groups of islands. These arches are several hundreds of kilometers wide and 1 to 2 kilometers high. Some of them are cut across by faults.

The largest arches, which are topped by numerous volcanic islands, are the swells of Karingamarangi Atoll (northeast of New Guinea), the Marshall and Gilbert Islands, Polynesia, Tuamotu Archipelago, Mid-Pacific, Marcus-Ne-

cker Rise, which runs along the Tropic of Cancer west of the Hawaiian Islands, and, finally, the Hawaiian Island. The Hawaiian arch stretches for 3 000 kilometers and is crowned with lofty flat-topped volcanic cones. Great sheet volcanoes such as Kilauea rise above sea level in this region. Since their bases lie at great depths, these volcanoes seem to be the highest active volcanoes on earth. The Hawaiian crest is disturbed by a trough which is superimposed on the arch and is the site of a volcanic chain.

Numerous seamounts and hills are distributed over the abyssal plains in the southwestern Pacific. Their shape is that of regular cones and heights range from several scores and hundreds of meters to thousands of meters above the ocean floor. These topographic highs are volcanoes in origin. Some of them rise above sea level, their heights reaching 10 or 11 kilometers and the diameter at the base varying between 5-10 and 70 kilometers. Some of the seamounts form clusters, rows, and short chains, while others are randomly distributed over the ocean floor. Their number runs into tens of thousands; thus, the Pacific is virtually packed with seamounts (F.P. Shepard). Many of them are flat-topped cones termed guyots; they are old extinct volcanoes that once stood above sea level and whose summits were cut off by sea waves and thus made flat. Then the truncated cones foundered deep in the sea. Interestingly, certain flat-topped cones proved to be very old. Some of them have been dragged from the top, and chunks of coral reefs of Cretaceous age have been lifted. These suggest that the volcanoes are pre-Cretaceous in age; therefore, the Mid-Pacific basin is very old.

The margins of the Pacific contain a clearly discernible system of island arcs which are included in the Circum-Pacific belt. This system is well developed along the Pacific coasts of Asia and Australia and is present in the American stretch of the belt.

Deep-sea trenches, closely related to island arcs, are major features of the Pacific floor, fringing and separting it on all sides from the Circum-Pacific fold belt. They extend along the island arcs off Asia and Australia and along the coasts of North and South America. The deepest are known to be the Mariana (11 034 meters), Tonga (10 882 meters), Kuril (10 542 meters), Philippine (10 497 meters), and Peru-Chile (8 066 meters). In places, for example, south of Japan and off the Pacific coast of Australia, as well as near the Antilles, they make up a second row but inside the Circum-Pacific belt. Deep-seated faults were found to cut into the earth's crust along the trenches, as indicated by numerous associated earthquake foci. Moreover, intermediate-focus (at depths of 60-300 kilometers) and deep-focus (deeper than 300 kilometers) earthquakes have been recorded in a zone stretching along the faults that cut through the earth's crust at a certain angle. The zone is inclined under the adjacent island arc or the continent.

Therefore, deep-sea trenches are surface manifestations of giant breaks that extend through the crust into the mantle and are active even now. It is the adjacent trenches that cause tremendous submarine earthquakes accompanied by floor disturbance and hence by huge tsunamis (off the Japan, Kuril, and Aleutian Islands). On the oceanward side, trenches are bordered by the above-mentioned marginal swells.

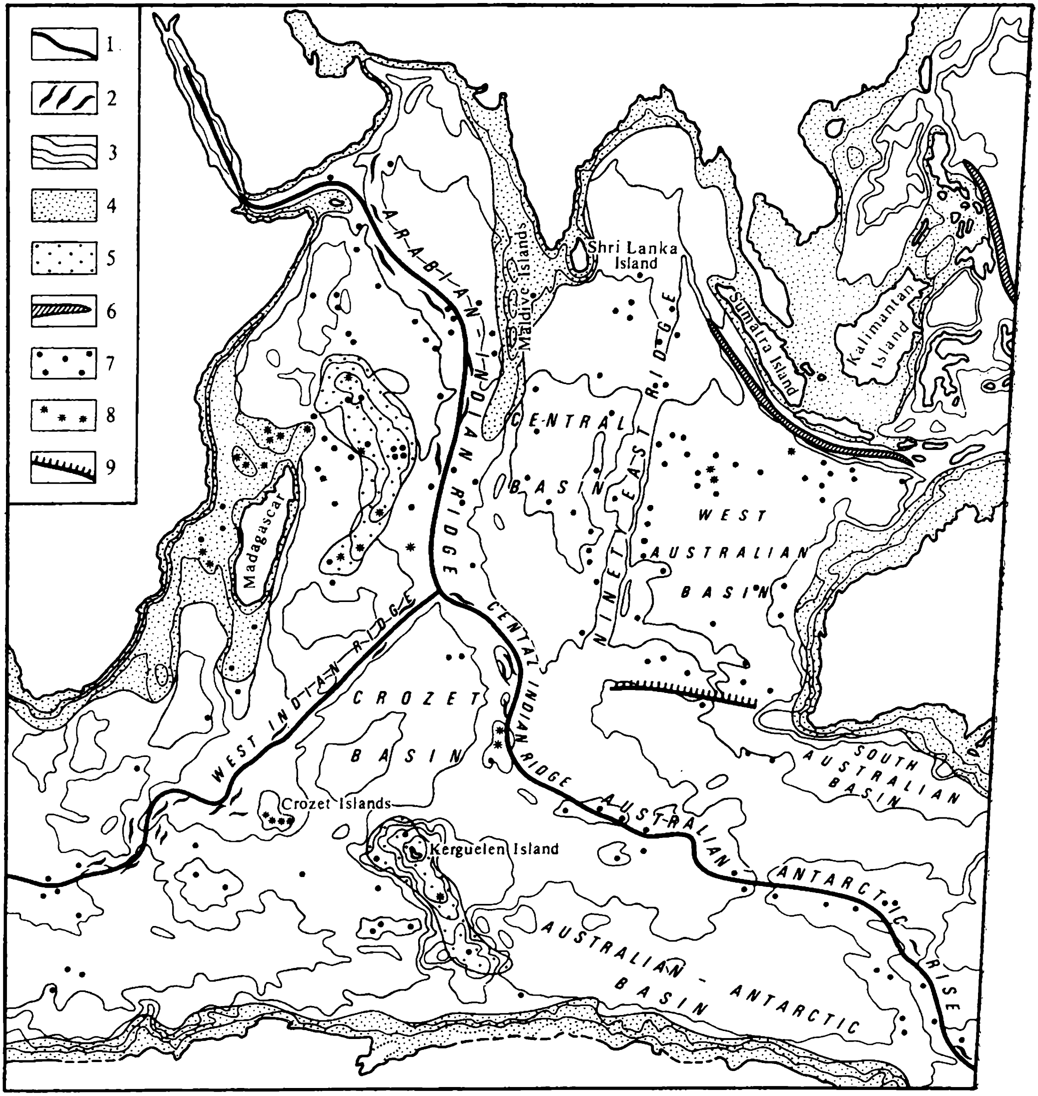


Fig. 32. Physiographic map of the Indian Ocean floor:

1 — rift valley of mid-oceanic ridge;
2 — isolated ridges;
3 — isobaths;
4 — continental shelf;
5 — ocean floor underlain by continental crust;
6 — deep-sea trench;
7 — seamounts;
8 — volcanic islands;
9 — major fault

Indian Ocean

In the past few years, the Indian Ocean floor has been studied rather thoroughly by the Soviet Research Ships *Vityaz* and *Ob* and several American and British research ships. Its topography and physiography has been recent-

ly described by P.L. Bezrukov, I.M. Beloussov, A.V. Zhivago, and V.F. Kanaev (1964), V.V. Beloussov (1968), and other scientists.

Unlike the Pacific, the Indian basin is diveded into a number of distinct variously shaped basins most of which are elongated and are 1 000 to 1 500 kilometers across. The basins are separated by submarine topographic highs—swells and ridges. The West-Indian, Central Indian, and Arabian-Indian Ridges are typical mid-oceanic ridges with rift valleys, high seismicity, and volcanism. The Australian-Antarctic Rise, Ninety East Ridge, and Madagascar Plateau are arches. The Mascarene-Seychelles Ridge and the Kerguelen Islands, which are block faulted, as shown earlier in the text, are underlain by the continental crust containing the granitic layer. Judging from its topography, the West Australian Ridge also consists of block mountains, although no granitic layer has been found there.

The abyssal plains separated by these ridges and swells are flat and lie at depths between 4 500 and 6 000 meters. Numbering 12 all in all, they have irregular oval shapes, although some of them have angular or curvilinear boundaries (Somali Basin) or are greatly elongated (Central Basin). Their location and shape are shown in the diagrammatic topographic map of the Indian Ocean floor (Fig. 32). The Indian basin is seen to basically comprise a system of depressions separated by submarine topographic highs.

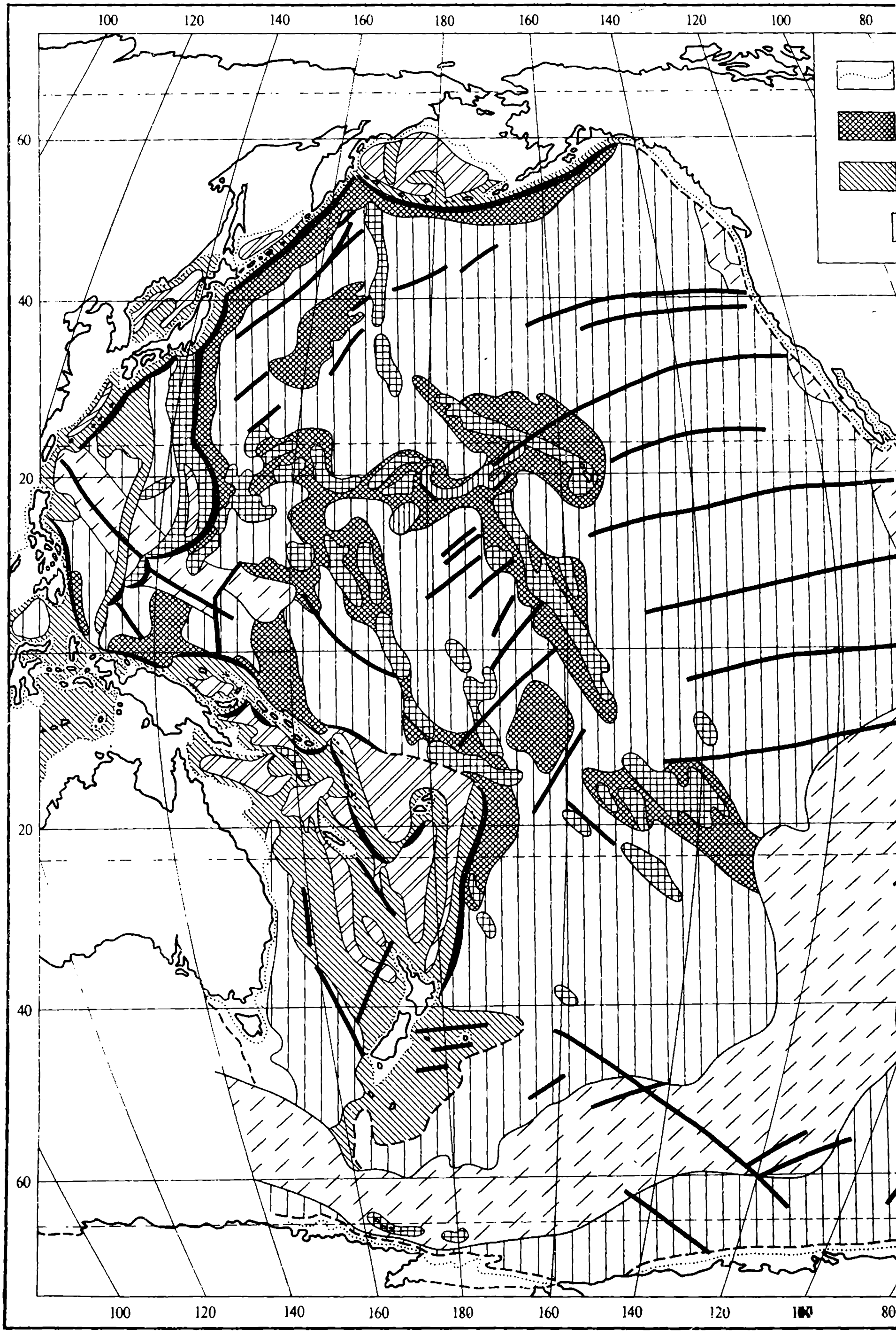
In addition, the Indian Ocean contains at its northeastern edge a single trench, which is more than 7 400 meters deep and runs along the Indonesian islands—Java, Sumatra, and others. It looks exactly like the Pacific trenches, particularly in shape, size, and high seismicity, and is probably of similar origin. In the east, this trench is arcuated along the line of small islands of the Indonesian Archipelago, such as the Tanimbar, Kai, and Banda Islands, and runs close to the Philippine and New Guinea Trenches, which fringe the Pacific. No other typical trenches are present within the Indian Ocean; nor are there island arcs and volcanic swells similar to the Hawaiian Ridge.

Atlantic Ocean

The elongate Atlantic basin, which is somewhat curvilinear in outline, is between America, Africa, and Europe. The basic subdivision of the oceanic physiography is the Mid-Atlantic Ridge which runs the length of the ocean and follows in curvature its coast line. All the ocean floor can be divided into two rows of basins which are parallel to the Mid-Atlantic Ridge, located between the ridge and the continental slopes of the neighboring continents, and separated from each other by submarine rises.

The basins are flat and occur at depths between 5 000-6 000 meters and 7 000 meters. The rises stand from 1 000 to 2 000 meters above the ocean floor, some of them being topped by volcanic cones which even project out of the ocean. The Mid-Atlantic Ridge gave rise to Bouvet and Tristan da Cunha Islands in the south; St. Helen, Ascension, and St. Paul Islands, and the Azores, in the middle stretch; and Iceland and Jan Mayen Island in the north (Fig. 33).

The deep-sea basins that border the Mid-Atlantic Ridge are located in pairs symmetrically about the ridge. These are, from north to south, the Greenland and Norwegian Basins, the broad North American and North Af-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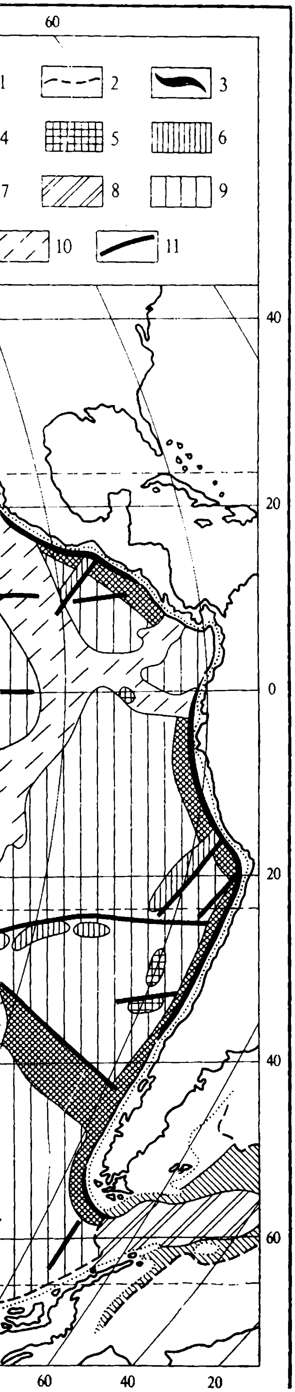


Fig. 31. The physiography of the Pacific Ocean floor (after G. B. Udintsev, 1972):

1 — outer edge of continental or island shelf;
2 — outer edge of transitional zone;
3 — deep-sea marginal oceanic trench;
4 — arches and swells;
5 — volcanoes;
6 — block mountain ranges on ocean floor;
7 — fold-block mountain ranges and massifs;
8 — basins of transitional zone;
9 — basins of ocean floor;
10 — mid-oceanic ridges;
11 — fault or fault-zone

rican Basins, which can be subdivided into smaller regions, and the Brazilian and Angolan Basins, which are separated from the southernmost Argentine and Africa-Antarctica Basins by the Rio Grande Rise and Walvis Ridge. The floors of the basins, especially those of the broad basins in the northern Pacific, are irregular, hilly, and are divided by ridges into minor basins.

Therefore, like the Indian floor, the Atlantic floor is subdivided into several basins having a typical oceanic crust and separated by topographic highs underlain by a somewhat thicker oceanic crust. The main feature of the ocean floor is the Mid-Atlantic Ridge, a magnificent mountain system more than 20 000 kilometers long. Numerous earthquakes are associated with it, indicating its great seismicity. The cones of islands, many of which are active volcanoes (Bouvet, Tristan da Cunha, Ascension, St. Helena, the Azores, and Iceland), and the basaltic fragments lifted from the ocean floor are evidence for volcanic activity. In the past few years, the topography and physiography of the ridge have been studied rather thoroughly (B. Heezen, M. Tharp, and M. Ewing, 1963). One of its major physical features proved to be a much greater heat flow ($7 \cdot 10^{-6}$ cal/cm$^2 \cdot$s).

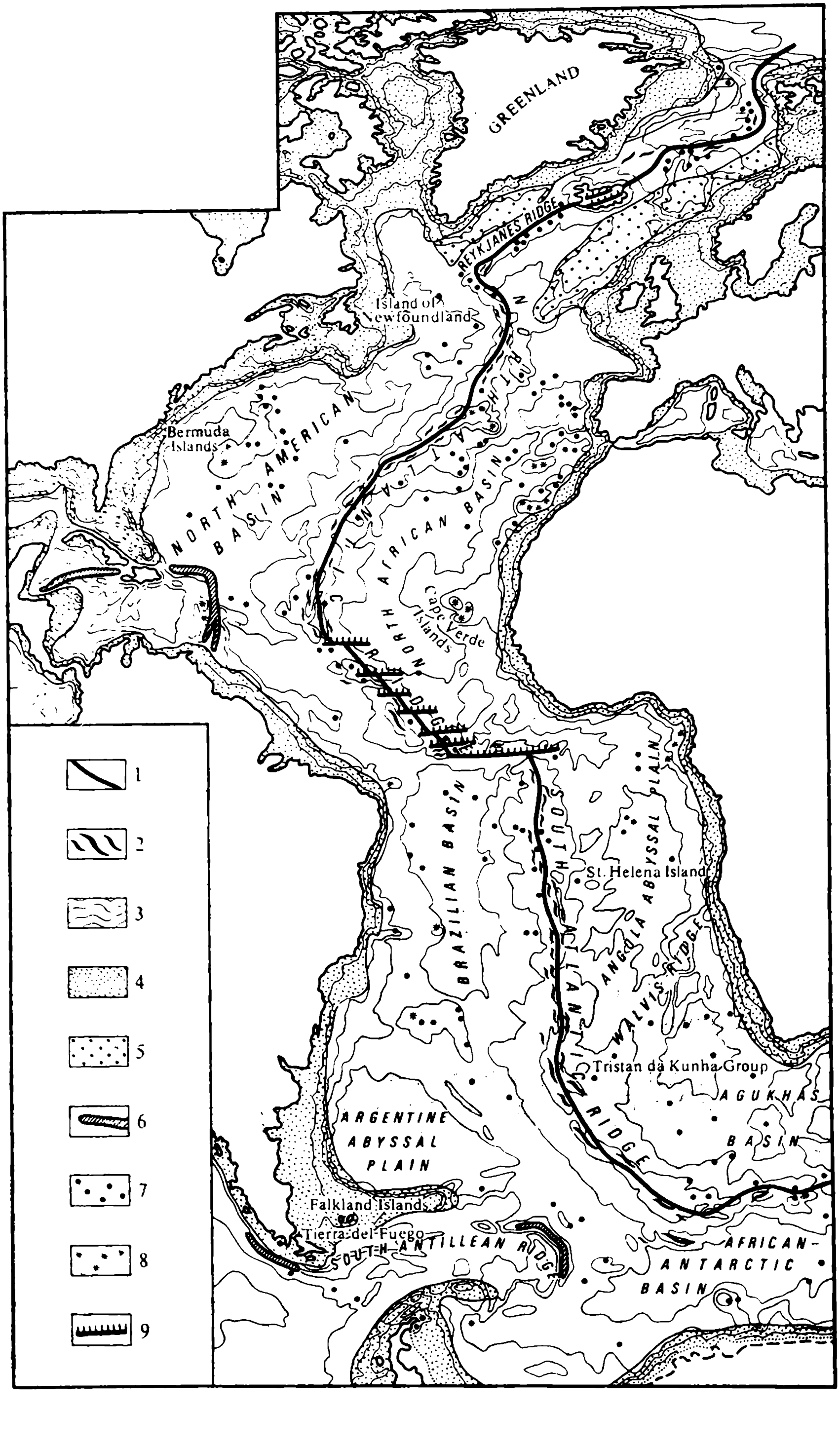
The Mid-Atlantic Ridge has quite an irregular topography and consists of a number of steep-sided steps, high fractured plateaus and ranges. A rift valley, and lofty rift mountains, which are upfaulted blocks, extend its length with interruptions. Some of the mountains project out of the ocean, such as St. Paul Island, composed of volcanic and ultrabasic rocks, and Iceland. The rift valley, a steep-sided depression with a flat bottom 30-40 kilometers wide, also originated from subsidence on fault planes.

In addition to the ocean floor, a study of Iceland can provide much geologic data on the Mid-Atlantic Ridge. This island is part of the ridge and contains a rift valley which extends, slightly bending, its length and is the site of the majority of active volcanoes. The rift valley is a direct continuation of an offshoot of the submerged rift valley belonging to the Mid-Atlantic Ridge. In Iceland, it is also a downfaulted graben filled with Quaternary and Recent lavas and volcanic tuffs. The valley is bounded by fault systems, and a fault system also follows its median line. Volcanoes and fissure lava outpourings are restricted to fault lines. The greatest lava outpouring took place in 1783-1784 through the Laki Fissure, nearly 25 kilometers long, in Southern Iceland. The volume of the poured-out lava reached 12-15 cubic kilometers. It covered an area of 565 square kilometers, and the evolving gases killed off much of the livestock in Southern Iceland, which caused widespread hunger among the population.

The flanks of the rift valley are formed of lava plateaus made up of older (Eocene to Pliocene) bedded lavas. According to geophysical evidence, they are underlain by more friable volcanic materials, tuffs and breccias, which have apparently originated from explosive volcanic activity on the ocean floor. Tuffs and other volcanic clastics seem to constitute the base of the Mid-Atlantic Ridge. Their thickness must exceed 6 kilometers, and they probably are of pre-Eocene or possibly of Cretaceous age.

Therefore, the Mid-Atlantic Ridge is a huge zone of a deep-seated fault.

West of the Atlantic Ocean lies the Caribbean Sea rimmed by the ridge of the Greater and Lesser Antilles which constitute a typical island arc with an adjacent deep-sea trench. Although these ridges and the trench are located


GREENLAND
REYKJANES RIDGE
Island of Newfoundland
Bermuda Islands
NORTH AMERICAN BASIN
NORTH ATLANTIC RIDGE
NORTH AFRICAN BASIN
Cape Verde Islands
BRAZILIAN BASIN
SOUTH ATLANTIC RIDGE
ANGOLA ABYSSAL PLAIN
St. Helena Island
WALVIS RIDGE
Tristan da Kunha Group
AGUKHAS BASIN
ARGENTINE ABYSSAL PLAIN
Falkland Islands
Tierra del Fuego
SOUTH ANTILLEAN RIDGE
AFRICAN-ANTARCTIC BASIN
1
2
3
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in the Atlantic, tectonically they make up a stretch of the Circum-Pacific belt. Similarly, the island arc of the South Sandwich Islands between Cape Horn and Antarctica (also accompanied by a trench) must be included in the Circum-Pacific belt.

Arctic Ocean

Soviet Arctic expeditions and drifting stations, beginning with the famous Papanin Expedition, have contributed much to the knowledge of Arctic floor physiography (D.G. Panov, P.M. Demenitskaya, A.M. Karasik, and G.G. Kiselev). Similar investigations have been undertaken by American polar expeditions.

Topographically, the Arctic Ocean basin is divided into the Canada and Fletcher Abyssal Plains, about 4 000 meters deep, and the Pole and Barents Abyssal Plains, more than 4 500 meters deep (Fig. 34). They are separated by three submarine ridges: the Lomonosov, which runs precisely through the Pole and divides the Arctic basin into two halves: the Alpha, between the Fletcher and Canada Abyssal Plains; and the Arctic Mid-Oceanic Ridge, which stretches between Greenland and Spitzbergen and separates the Barents and Pole Abyssal Plains. R.M. Demenitskaya (1967) indicates that evidence is available for the existence of another ridge in the Canada Abyssal Plain.

Although the Barents and Pole Abyssal Plains are small, they are similar to the abyssal plains of the Atlantic and have an oceanic crust. The smaller Fletcher and Canada Abyssal Plains are underlain by the crust, 15 to 20 kilometers thick, containing, according to geophysical evidence, patches of a granitic layer. This crust contains occasional "windows" 10 kilometers thick. Thus the crust beneath the Arctic basin is much thicker than that beneath the other ocean basins.

The Earth's crust underlying the Lomonosov and Alpha Ridges is even thicker, reaching 15-18 kilometers. We cannot rule out the possibility that they contain regions of the granitic layer, which allows us to refer to them as block mountains. In particular, the Lomonosov Ridge rises on the continental crust.

B.C. Heezen, R.M. Demenitskaya, and other scientists believe that the Mid-Atlantic Ridge, and its rift valley, continues into the Arctic Ocean, though it is not very clearly discernible there. The mid-oceanic ridge is inferred from the zone of earthquake foci running between the Barents and Pole Abyssal Plains, where occasional high swells stand above the ocean floor.

The continental shelf of the Arctic Ocean off the Asia and Europe is the broadest in the world. Eurasian structures extend into the shelf which is underlain by the continental crust.

Geologic evidence indicates that great differences exist between the coasts of the Pacific, on the one hand, and of the Atlantic, Indian, and Arctic, on

Fig. 33. **Physiographic map of the Atlantic Ocean floor:**

1 — rift valley of mid-oceanic ridge;
2 — isolated ridges;
3 — isobaths;
4 — continental shelf;
5 — ocean floor underlain by continental crust;
6 — deep-sea trench;
7 — seamounts;
8 — volcanic islands;
9 — major fault

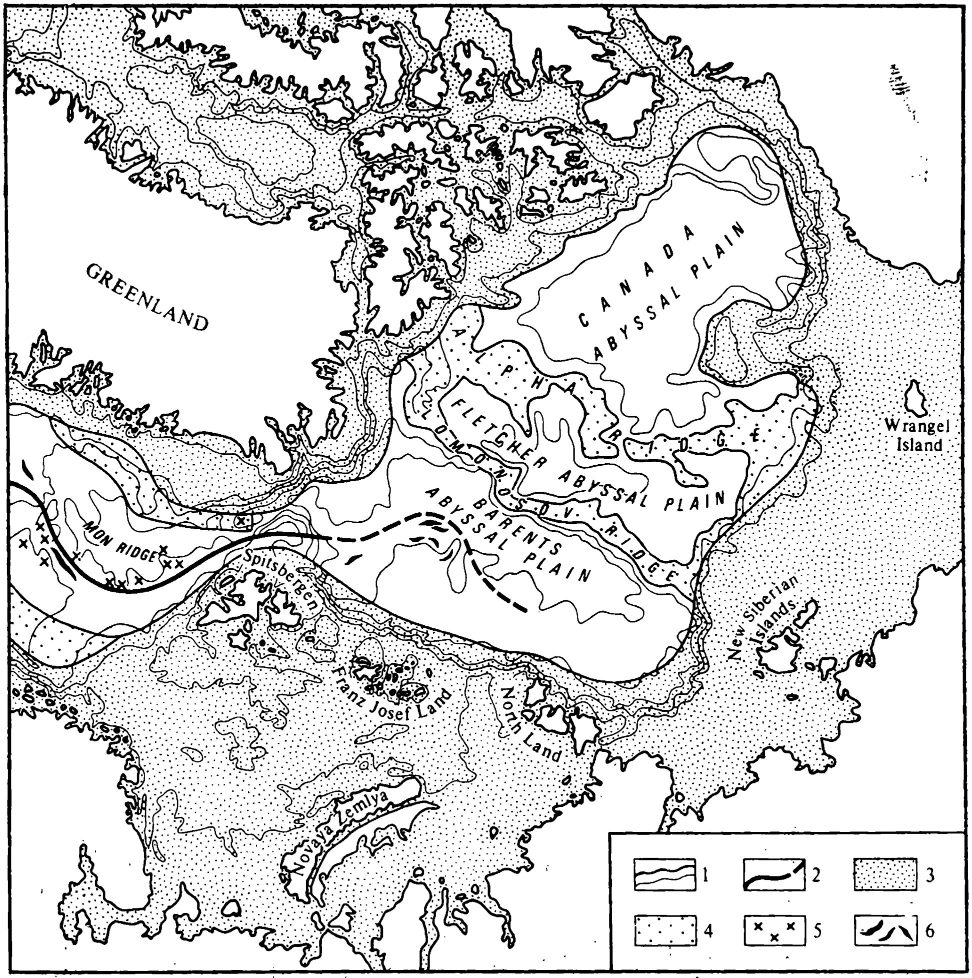


Fig. 34. Physiographic map of the Arctic Ocean floor:

1 — isobaths;
2 — rift valley of mid-oceanic ridge;
3 — continental shelf;
4 — ocean floor underlain by continental crust;
5 — seamounts;
6 — isolated ridges

the other. Proceeding from these differences, E. Suess distinguished the Pacific and Atlantic types of coast, V.I. Vernadsky advanced the concept of "asymmetry of the globe", and N.S. Shatsky wrote about the features of the "earth's Pacific segment."

The distinction lies, above all, in the fact that the Pacific floor is successively fringed by the most recent to progressively older Circum-Pacific geosynclinal fold areas, with the inner zone represented by the island arcs associated with deep-sea trenches.

In contrast, the Atlantic, Indian, and Arctic coasts cut off, at a rightangle or obliquely, the ancient platforms and fold areas of the adjoining continents.

IX

THE ORIGIN OF OCEAN BASINS IN THE LIGHT OF GEOLOGIC EVIDENCE

The generation of the ocean basins, gigantic depressions of the earth's surface, cannot be seen directly or simulated in the laboratory. Finding out the causes and history of this process, we should take into account all the natural phenomena occurring during the evolution of the earth's crust, including deformation, igneous activity, and metamorphism. Observations of the earth's crustal surface, together with geophysical evidence on the earth's interior, can only help yield a more or less clear understanding of the origin of ocean basins, one of the most complex problems in modern geology and geophysics.

It is no wonder that there are numerous hypotheses explaining their origin. We are only just beginning to learn something about the earth's interior and do not as yet know enough about the processes to put forward a coherent theory.

THE PHYSIOGRAPHY OF THE PACIFIC BED AND ITS PROBABLE ORIGIN

The Pacific is known to be distinguished by a concentric arrangement of its surrounding fold areas. In addition, the floor of the Mid-Pacific and the Eastern Pacific is underlain by the thinnest crust. According to geophysical recordings, the thickness of the earth's crust varies there mainly between 4.8 and 7.46 kilometers, reaching 10 to 18 kilometers within some submarine rises.

R.M. Demenitskaya's map of the Pacific Ocean (1967) shows the crustal thickness at different places and indicates that the crust gradually thins

Fig. 35. Thickness (km) of the Pacific floor crust (after R.M. Demenitskaya)

inward under the Eastern Plain between Polynesia and America (H. Raitt's data). At 7°20′ S and 118°40′ W, the crust is the thinnest (4.85 kilometers). To the northeast and southwest the crustal thickness gradually increases to 5, 6, 7 kilometers or more (Fig. 35). The basaltic layer is 3.14 to 5.69 kilometers thick between the Marshall and Hawaiian Islands, 4.42 to 6.24 kilometers thick between the Hawaiian Islands and North America, and 3.31 to 9.58 kilometers thick in the tropical part of the ocean.

According to I.P. Kos'minskaya, the basaltic layer under the Pacific can be subdivided into the upper unit, with seismic wave velocities between 6.3 and 6.9 kilometers per second, and the lower unit, with velocities between 7.0 and 7.3 kilometers per second.

In Melanesia and Micronesia, western Pacific, the crustal thickness varies greatly from 5-6 to 8.66-12.55 kilometers within some basins on submarine rises and near the lines of islands, such as the Marshall Islands. This shows that these lines are related to local thickening of the earth's crust. The second layer thickens greatly in some places, for example, to 4.38 kilometers near the Annventok Atoll and 5.60 kilometers in the vicinity of Nauri Island, the southern end of the Caroline Arc continuation, while it is 1 to 2 kilometers thick elsewhere. The second layer consists of slightly compacted

tuffs alternating with basaltic lavas. The longitudinal wave velocities through them vary between 3.5 and 5.5 kilometers per second. Its presence suggests extensive lava outpourings which may have repeatedly taken place in this area of the Pacific.

The Pacific floor is crowded with seamounts, some of which are associated with swells while others are distributed in between. The huge Hawaiian volcanic swell is the greatest, and its volcanoes are lofty.

Numerous volcanic cones and guyots, some of them being crowned with coral reefs or forming atolls, rise above the southwestern Pacific floor. H.W. Menard (1964) has correlated the heights of guyots now submerged at different depths. Their summits are truncated by wave action, and the platforms thus formed possibly correspond to an ancient sea level. Having compared their present position at different depths below sea level, H.W. Menard has found that the volcanic cones had their summits truncated while standing above a very extensive archlike rise. It stretched for 10 000 kilometers from the southeast to the northwest and was as wide as 4 000 kilometers. By reconstructing its oval shape from guyot heights, Menard determined that the ocean depth was as much as 3.5 kilometers at the axis of the rise and 5-5.5 kilometers on its margins. He has named this ancient rise the Darwin Rise, in honor of the great naturalist who was the first to develop a valid theory of coral atoll origin.

The Eocene and Late Cretaceous ages of the coral reefs on some of the guyots suggest that the volcanoes, and hence all of the Darwin Rise, were generated till mid-Cretaceous time (more than 100 million years ago) apparently early in the Mesozoic. The rise evidently developed as a gentle-sided, gigantic bulge of the mantle which upheaved the earth's crust. As a result, the crust was broken up by a network of longitudinal and transverse fracture zones giving rise along them to volcanic outpourings and cones.

Later, in the Cenozoic, most of the Darwin Rise subsided, except for some areas such as the base of the Takelau Islands. Unimaginably extensive and copious volcanic eruptions were associated with the Darwin Rise. It is here where the volcanic layer of the earth's crust is thicker than elsewhere.

The rise had formed by mid-Cretaceous time and began to disappear after Eocene time. At least some of the submarine highs topped by the islands of Melanesia, Micronesia, and Polynesia can be regarded as remnants, or fragments, of this rise.

This is the picture of the development and disappearance of the ancient rise on the ocean floor, which was apparently a special type of structure. Many scientists, however, have recently concluded that Menard's data do not support the conception of the ancient Darwin Rise.

We cannot rule out the possibility, however, that the Mid-Pacific chains of islands, where basic volcanic rocks occur (basalt-peridotite and nepheline basalt outpourings), represent the very beginning of the geosynclinal cycle, with the lines of volcanic islands localized in the zones of deep-seated faults cutting through the oceanic crust.

The system of the western Pacific island arcs, including the islands of the Aleutian and Kuril arcs, and the Bonin, Ryukyu, Mariana, Solomon, Admiralty, New Hebrides, Fiji, Tonga, and other islands is distinguished from the Mid-Pacific by andesitic outpourings suggesting more acidic magma

chambers in the earth's crust. Along with other evidence, this indicates that a thicker, though patchy, transition-type crust occurs there. The area includes several true geosynclinal areas in the stage of island arcs separated from the Pacific floor by an extremely clear-cut garland of trenches coinciding with the "andesitic line".

The island arc areas make up the inner zone of the Circum-Pacific belt, which is followed outward by the areas of the Cenozoic folding and volcanism on the Pacific coast.

Here we get the geosynclinal areas undoubtedly in a more mature phase than in the previous zone. Along with vast and deep geosynclinal troughs, these areas contain large mature uplifts, or anticlinoria, such as New Guinea, the Philippines, Taiwan, and Japan. As illustrated by the data presented in a number of recent studies of the geology of Japan, the Philippines, and other regions, the distinction lies not only in the depth of sinking below sea level, but also in much more extensive anticlinal uplifts formed during long time intervals.

Next is the zone of the Mesozoic folding of the Verkhoyansk area, Alaska and the Rockies, where the geosynclinal cycle has long come to an end and a young epi-Mesozoic platform has originated. Here, the basement is highly elevated, and a true sedimentary cover does not begin to accumulate.

A certain pattern can be seen in the concentric arrangement of the areas underlain by different types of crust. The Pacific ocean is successively rimmed by fold structures of various ages, from the youngest island arcs, rising above the ocean floor, to the older Mesozoic fold structures.

Therefore, the Circum-Pacific belt demonstrates a succession of stages of crustal evolution from pre-geosynclinal conditions of an oceanic plate through early oceanic ridges and the geosynclinal stage of island arcs and then of large islands and mountain ranges underlain by a transition-type crust to the stable Mesozoic fold belts of the Far East and North America.

The floor of the Mid-Pacific and the eastern Pacific is genetically connected with the succession of the fringing zones. Here, the crust is probably in the early, pre-geosynclinal stage of development and hence completely lacks the granitic layer.

Geographically, the Pacific coasts reflect a close relationship between the ocean floor and the Circum-Pacific geosynclinal areas. That the Pacific floor is encompassed by these zones indicates that the fold areas originated one after another at the expense of the margins of the ocean floor which concentrically shrunk with time and with the growth of new peripheral zones of fold mountain chains.

Consequently, the Pacific margins are in line with the hypothesis that the middle of the ocean may be underlain by the earliest crust. It is rimmed by the areas that were successively involved in the geosynclinal cycle, and the outermost ones were stabilized, on the completion of the cycle, to form the basement of young continental platforms.

The data available on the old age of the Pacific basin also conforms with this conception. We have already mentioned that some of the guyots are topped by Cretaceous coral reefs. That the Darwin Rise, with tremendous volcanic manifestations on its surface, had formed by the middle of the Cretaceous shows clearly enough that the Pacific Ocean did exist early in the

Mesozoic, that is in the Jurassic and Triassic. In fact, there is no ground to deny its existence as far back as Paleozoic time. According to Menard, volcanism was then much weaker within its limits than during Mesozoic time.

A. Wegener (1924), A.D. Arkhangel'sky (1941), N.M. Strakhov (1948), and many other distinguished scientists argued that the Pacific floor is the most ancient area of the earth's crust. G. Stille (1946) thoroughly substantiated this view and concluded that the Pacific Ocean basin should be classified as a primary basin generated in the remote Precambrian. He was the first to distinguish the most ancient from the new secondary ocean basins.

Later (1957), in light of the more recent evidence available, the author of this book also tried to substantiate the hypothesis that the Pacific Ocean basin is of Precambrian age. The tectonic map of Eurasia (Yanshin et al., 1966) reflects this view. After an analysis of the tectonics of the Pacific coasts and the Circum-Pacific belt, Yu.M. Pushcharovsky (1966) shares the opinion on the ancient origin of the Pacific. In support of this opinion, several scientists, including N.A. Bogdanov (1969), have found a number of thalassogeosynclines in several peripheral regions of the Pacific. Thalassogeosynclines are geosynclinal troughs initiated and developed in the oceanic crust and filled with a specific complex of metamorphosed basic volcanic, siliceous, and greywacke formations. The thalassogeosyncline of the Coast Ranges in California is filled with the Franciscan formation of Late Jurassic to Early Cretaceous age. The similar rocks of eastern Sakhalin, Hokkaido, and the eastern margin of the Koryak Highlands are of Permian, Jurrassic, and Early Cretaceous age. The greywacke and volcanic rocks of New Zealand formed within a wider time span (Carboniferous to earliest Cretaceous) and underlie younger sediments. Similar rocks are known in the core of an anticlinorium in New Caledonia. These rocks on the western and eastern margins of the Pacific are Mesozoic, Permian and even Carboniferous in age, which suggests that at the end of the Paleozoic and the beginning of the Mesozoic the ocean floor and oceanic crust were broader than they are now. Hence this proves the existence of the Pacific Ocean basin in the late Paleozoic and a gradual contraction of its area. Moreover, this is an additional argument in favor of the probable earlier existence of the Pacific Ocean, that is, at the end of the Proterozoic or at the beginning of the Paleozoic.

That the Pacific basin is ancient is confirmed by interesting and convincing data derived from an analysis of the abyssal life of the ocean. In the opinion of L.A. Zenkevich and Ya.A. Birstein, the animal life of the ocean is an integrated system which evolved for quite a long time. No new type of organism appeared throughout the Phanerozoic. Hence we must admit the great age of the oceans, or at least some of them, as the environment in which the animal kingdom evolved.

All the above indicates that the Pacific bed can be regarded as a remnant of a very ancient primary oceanic crust which once covered the entire globe before the formation of the oxygen-nitrogen atmosphere of the earth. Like the lunar crust, the original crust consisted of basic igneous rocks which later gave rise to the earth's basaltic layer. This layer makes up the bulk of the present Pacific Ocean bed and is covered there by younger volcanic rocks and

a bed of marine sediment. The latter was laid down so slowly that it is thin (2-3 kilometers) in spite of the extremely long time of sedimentation. The crustal basaltic layer also did not remain unchanged. It experienced to a greater or lesser extent the action of volcanism, metasomatism, and metamorphism.

THE PHYSIOGRAPHY OF THE ATLANTIC, INDIAN, AND ARCTIC BEDS AND THEIR ORIGIN

The physiography of the Atlantic. Indian, and Arctic floors and the surrounding coasts differs greatly from that of the Pacific floor and its coast.

The Atlantic basin is "superimposed", as it were, on the structures of the adjoining continents. It is completely alien to them, overlapping and cutting off the widely differing tectonic elements of the continents. The eastern Atlantic coast first cuts off the Caledonian fold areas of the Atlantic belt in Norway, the United Kingdom, and Ireland and then the fold structures of the Hercynian area of Brittany and the west coast of France (the Mediterranean belt). To the south, it hacks almost across the Alpine fold area of Southern Spain, the Paleozoic structures of Northern Africa (Atlas) and the Iberian Peninsula, which have no traces of extension on the ocean floor, and even farther south it cuts off the ancient platform-type structures of Africa. The western edge of the basin is superimposed on the Caledonian and Precambrian structures of Greenland, the Caledonian structures of Newfoundland, the interior massifs of the Appalachians, the Guiana shield of Archean age, and the late Proterozoic fold area of the Brazilides and Patagonia massif.

This is the most important and interesting feature of the Atlantic Ocean basin. If it were completely superimposed on a uniform platform of, say, Precambrian age, such as the Gondwana platform, we would anticipate that after the subsidence of the platform the basin floor would have been more or less homogeneous. But inasmuch as such heterogeneous entities subsided in the basin as a part of the Precambrian platform of Gondwana, several stretches of the Alpine geosynclinal area, and the Paleozoic fold areas of Western Europe and North America, the absence of at least slight differences in the topography of the Atlantic floor needs explanation.

In fact, on the continents of Europe and America these basic tectonic elements differ very widely in tectonics, geologic history, neotectonic crustal movements, and hence topography; yet they have no counterparts on the ocean floor. All its features have no bearing on the tectonic elements of continents, but, on the contrary, are symmetrical as to the general outlines of the Atlantic coasts. The Mid-Atlantic Ridge is S-shaped in line with the general configuration of the ocean coasts.

The topography of the Atlantic floor cannot be explained in terms of the simple subsidence of fault blocks of the continental crust within ancient and young platforms and the Mediterranean belt and requires some other explanation.

The concept that continental blocks have simply subsided on the Atlantic floor is even more open to objections in the light of the geophysical evidence on the earth's crust beneath this ocean. It has been known for a fairly long time that the Atlantic, Indian, and Pacific have large positive gravity anomalies. It was erroneously believed, however, that the crust beneath the Atlantic and Indian floors resembles that beneath the continents and differs from the crust beneath the Pacific Ocean.

Recent geophysical investigations of the Atlantic floor have shown that the crust does not basically differ there from that underlying the Pacific floor. According to the American oceanologists J.B. Officer, M. Ewing, and R. Winchell, between 400 and 600 kilometers south of the Bermudas the earth's crust is slightly more than 10 kilometers thick and becomes thicker toward the islands.

Seismic investigations have revealed that the broad area south, southwest, and northwest of the Bermudas, with depths of 5 to 6 kilometers, has a very thin crust, also 5 to 6 kilometers thick. The thin, 5- to 6-km oceanic crust also occurs north of Puerto Rico, its thickness increasing rapidly toward the island.

The earth's crust is even thinner beneath the rift valley of the Mid-Atlantic Ridge. It contains areas completely lacking crust and, instead, underlain by a thin sedimentary cover resting directly on the mantle. It is these mantle outcrops that are thought to be mantle protrusions, such as St. Paul Island, near the equator, made up of volcanic and ultrabasic rocks*.

Recent investigation, however, has revealed broad continental areas of the northern Atlantic floor that have, though not thick, a granitic-metamorphic layer. Two of them are north of Norway and Scotland and southeast of Greenland, and the third is the Blake Plateau off North America.

D.Yu. Sutton (1954) found that from the Bermudas toward New York and Washington the crust is gradually thickening while the ocean is becoming shallower, and that a granitic-metamorphic layer appears 300 to 500 kilometers from the coast. It is 3 kilometers thick southeast of Newfoundland and 8 kilometers thick at the same distance from Halifax Island.

A thin granitic-metamorphic layer has been discovered under the ocean floor 200 kilometers off eastern South America, near the mouth of the La Plata River. As V.V. Beloussov (1969) points out, the broad margin of the abyssal Atlantic off North America was for a long time a shallow-sea continental shelf which has been subsiding since Late Cretaceous time. As late as the beginning of the Neogene this area of the ocean floor sank to the present depth, the above-mentioned submarine Blake and Bahamas Plateaus being shelf remnants that have not subsided to abyssal depths.

The Indian floor is physiographically similar. Its basins have no genetic relationship to the surrounding coasts. On the contrary, these basins are obviously superimposed on the coastal structures that are completely different in origin and age. The edge of the Indian Ocean floor cuts off the platform-type structures of the African, Indian, and Australian platforms and

* The strontium dating obtained in 1964 by the Carnegie Institute of Technology on six mantle-derived mylonitized peridotites from St. Paul Island shows that four of them are about 4 500 million years old.

Madagascar, and the structures of their Precambrian basement. An exception is observed between the Bay of Bengal and Australia, where the edge of the Indian Ocean conformably adjoins the chain of the geosynclinal structures of Indonesia, the Nicobar Islands, and the Andamans. They are parallelled by a distinct narrow gash which passes northward into the foredeep of the Arakan anticlinorium in Burma—the depression in the lower Brahmaputra River area.

The above stretch of the Indian edge is the only one that is conformably fringed by the Indonesian geosynclinal area and its foredeep, rather than cuts off coastal structures.

In the deeps of the Indian Ocean, the earth's crust is not more than 10 kilometers thick. On the flanks of the Mid-Indian Ridge, the basaltic layer is thinner than elsewhere and, according to G.B. Udintsev, is absent in some places near its crest, within the rift valley. In some areas of the rift valley, loose sediments rest directly on the mantle. Moreover, *Vityaz*'s dragging from the rift valley sides has produced chromite-containing chunks of ultrabasic rocks derived from the mantle surface.

The Indian Ocean floor also contains broad areas underlain, as has been recently found, by continental crust. These are the Chagos Archipelago area and a rise to the north, including the Maldives, bordered by the shelf off southern Hindustan; the submarine rise of the Mascarene Islands and Seychelles, off eastern Africa; and the rise around the Kerguelen Islands in the south.

The Arctic Ocean edges also cut off the tectonic elements of the surrounding continents: the Arctic belt of America, the Mesozoic structures of northern Siberia, and the Atlantic belt.

As mentioned above, the Arctic floor differs from other ocean floors in the occurrence of the granitic layer of the crust beneath broad regions of basins and submarine ridges. Remnants of the continental crust are numerous there.

All this discards the hypothesis that the Atlantic, Arctic, and Indian floors are primary in origin and that we have here a thalassocraton, like that of the Pacific, in the pregeosynclinal stage of the crustal history. On the contrary, the data support the view that these oceans are secondary and originated in the site of the earlier continental masses whose remnants make up the above areas of the floor underlain by continental crust, as typified by the Atlantic.

All the hypotheses of the secondary origin of ocean basins try to explain the geophysically detected absence of the continental crust beneath the ocean floors. Some theories explain this as a result of the complex conversion of continental crust into oceanic crust, the former becoming heavier, or oceanized, as some call it.

Other hypotheses explain the basic differences between the continental and oceanic crust as a result of the break-up and motion of crustal plates, a new oceanic crust being generated between the spreading plates.

Still other hypotheses attribute the origin of the oceanic crust to the earth's expansion and hence to the increase of its volume and surface, while the oceanic crust is considered newly formed.

HYPOTHESES EXPLAINING THE CONVERSION OF CRUSTAL MATERIAL BENEATH THE OCEAN FLOOR

A.D. Arkhangel'sky was the first to substantiate the hypothesis of the origin of ocean basins by the conversion of continental crust into oceanic crust. He suggested that the oceanic crust had been melted through by so many basic intrusions overlain, in addition, by volcanic rocks, that it had lost the properties of continental crust.

Subsequently V.V. Tikhomirov considered the basification of continental crust, with its conversion into oceanic crust as a result of basic metasomatism, that is, the withdrawal of fluids from the mantle to replace and thus oceanize the granitic-metamorphic layer.

V.V. Beloussov (1968) further developed and elaborated the basification hypothesis. He argued that all the ocean basins, including the Pacific, are of a later, secondary origin.

V.V. Beloussov believes that the globe was initially covered by a continental crust whose thickness varied somewhat from place to place. No oceans were present on earth till the end of the Paleozoic, and only at the end of the Paleozoic or the beginning of the Mesozoic did the molten mantle material, concentrated under the would-be ocean basins, began to rise as huge diapirs through the continental crust onto its surface. The intrusion of the earth's crust by the mantle material led to the formation of the present-day ocean basins which completely differ from continents in crustal composition and structure. At the same time, many scientists outside the USSR think that convection currents in the mantle can even tear off blocks of the crustal base and transport them to great distances. V.V. Beloussov believes that such large-scale convection does not take place in the mantle. The molten mantle material comes upward (vertically or at an angle) only through a fault zone (channelway), intrudes the earth's crust, solidifies there and partially transforms it into a heavy metamorphic rock, and finally sinks, together with that rock.

As a result, the continental crust is basified and converted into oceanic crust. According to Beloussov, this process ceased in all oceans at the beginning of early Cretaceous time. In the Atlantic and Indian Oceans, it operated from their margins inward, and still continues at the mid-oceanic ridges. In the Pacific, on the contrary, the basification involved the areas from the center outward, and the ocean basin gradually expanded at the expense of continental margins. It was superimposed there on the geosynclinal process still going on in the Circum-Pacific belt to produce the unusually complex structures of the Pacific periphery.

Although Beloussov paid attention to tectonic differences between the Pacific and Atlantic basins, he did not note that the structural units of the adjacent continents have different histories, as seen from the fact that they concentrically rim the Pacific, but are cut off by the Atlantic, Indian, and Arctic coasts.

At the same time, Beloussov showed that the Pacific exhibits volcanism and seismicity mainly at its margins while the Indian and Atlantic at their respective mid-oceanic ridges.

Beloussov extends the conclusion, supported by this writer, that the Atlantic, Indian, and Arctic basins are secondary in origin to cover also the Pacific basin which can on many grounds, as mentioned above, be regarded as extremely ancient and primary in origin.

We could try to explain the secondary basins of the Atlantic, Indian, and Arctic Oceans in terms of the conversion of the granitic-metamorphic layer by the compaction of the crustal material, as earlier described by S.I. Subbotin concerning the origin of syneclises, broad depressions of platforms. This hypothesis, however, is much more difficult to apply to ocean basins. Indeed, it implies that a thick continental crust had previously existed there, and a process operated that converted the crust into a material showing an affinity not only for the geophysically detected basaltic layer, but also for the physical properties of mantle material.

If, according to the above scheme, we can visualize the disappearance of the basaltic layer as it is replaced by eclogite whose physical properties are the same as those of the mantle, then the same approach to the granitic-metamorphic layer implies only its conversion into the granulite facies whose properties are those of the basaltic layer, not of the mantle.

Meanwhile, the geophysically detected basaltic layer beneath the ocean floor is thin (4 to 8 kilometers), while the continental granitic-metamorphic layer of the earth's crust can be much thicker. We should assume, therefore, that the latter has partially been converted into the material whose physical properties are the same as those of the mantle. This process, however, is difficult to imagine. We are forced to turn, in this case, to the basification hypothesis and consider that material compaction must have been accompanied by the introduction of basic material from the mantle interior to account for heavier and denser massifs.

Many geologists and geophysicists have concluded that the conversion of continental into oceanic crust is extremely difficult, if not impossible, to explain (V.A. Magnitsky, E.N. Lyustikh, and others). That is why we are forced to seek the reasons why the secondary ocean basins were generated in one of the versions of the hypotheses that continental plates were split up and pushed aside or in the expanding earth hypothesis.

MOBILISTIC HYPOTHESES INVOLVING CONTINENTAL DISPLACEMENT

The continental displacement hypothesis was brilliantly substantiated by A. Wegener (1929), a German geophysicist who lost his life during his expedition to Greenland. At that time nothing was known about the Moho, hence Wegener proceeded from the contemporary assumption that the earth's lithosphere consists of two thick layers termed sial (an acronym for silica + + alumina) and sima (an acronym for silica + magnesia). The sial, the

upper layer, roughly corresponds to the continental crust. According to Wegener's isostatic principle, it floats, like giant ice-floes, above the sima, its roots slightly bulging downward. That the Atlantic coasts of Europe and Africa so perfectly match with those of North and South America prompted A. Wegener to propose that these continents, separated now by the ocean, previously constituted a single continent. He considered the already known Mid-Atlantic Ridge the remnant of a welt from which the continents moved westward and eastward. Wegener attributed the fold chains of the Cordilleras and Andes to the westward movement of the continental plate.

The Wegener hypothesis was soon widely accepted in the USSR and elsewhere. It provided clues for botanists and zoologists to the similar development of flora and fauna on continents separated by oceans. The hypothesis was elaborated mainly by geologists working in Africa and Australia, who used it to explain similarities in the structure and history of these continents, parts of a once single Gondwana. Many scientists, however, pointed to a number of discrepancies between the concepts of this mobilistic hypothesis and the facts available. Thus, N.S. Shatsky has pointed out that some earthquake foci in the Circum-Pacific belt lie at depths from 200 to 300 kilometers, occasionally even to 500 kilometers. They have been found to be associated with fault zones dipping obliquely into the mantle. Termed the Benioff zones, these deep-seated faults, extending through the earth's crust into the upper mantle, contradicted the continental drift hypothesis.

On the whole, the horizontal displacement concept was not widely accepted for a long time. It has gained wide recognition, with modifications, only since late 1950's and early 1960's.

While A. Wegener believed that the earth originally contained a single huge continent of Pangea which then splitted up into pieces pushed aside over different distances, new modifications have envisaged different combinations of original continental blocks, assuming not only the horizontal, but also rotational movement of separate continental masses.

Several hypotheses assume that at the beginning of the Mesozoic the Hindustan Peninsula block lied centrally in the area now occupied by the Indian Ocean, but then moved northward and thus caused the rise of the Himalayas, fold mountains that originated from the displacement of a platform block in front of the Indian block.

Most hypotheses now admit that blocks do not move on the interface between the mantle and the crust, but on the deeper surface of the asthenosphere, the molten layer of the mantle, under the influence of convection currents, or circulation, in the asthenosphere. The rising convection currents are considered to be restricted to mid-oceanic ridges and are responsible, therefore, for their greater heat flow, while the descending currents occur beneath continents. It is the circulating convection currents that catch the abovelying blocks of mantle and crust and move them horizontally.

Some suppose, however, that such movement occurs on a surface at a depth of an order of 1 000 kilometers. Thus, R.W. Van Bemmelen, the famous Dutch geologist, has offered a hypothesis (1933) postulating that at the lower-upper mantle boundary, processes in the lower mantle generate huge bulges and depressions termed megaundations. Masses of the upper mantle and crust are moved by gravity down the slopes of positive undations. In Bem-

nelen's opinion, this results in the lateral movement of continents together with part of the mantle, the raised parts of megaundations being located immediately beneath mid-oceanic ridges and the lowermost parts, beneath continents.

A.V. Peive and his assistants are among those who recognize great lateral displacements of the crust. He believes that the floors of all oceans are in the earliest stage of the geosynclinal cycle. Next follows the stage of island arc generation and the sinking of related geosynclinal troughs. They are produced by major lateral displacement of cristal blocks on systems of inclined fault planes such as Benioff fault planes. These blocks are shoved against each other to build up the basaltic layer and then granitize it and at the same time thicken the granitic-metamorphic layer. The oceanic crust moves apace with the generation of new areas of the ocean floor. A major distinction of this hypothesis lies in the fundamental concept that during the geosynclinal cycle the oceanic crust is converted into the continental crust.

In the past few years, after new data were obtained on the geology and geophysics of the ocean floor, particularly of that beneath mid-oceanic ridges, as briefly described above, several mobilistic concepts and generalizations have been put forward representing a radically new theory. This theory has been called "plate tectonics", or "new global tectonics", and its fundamentals were introduced several years ago by B. Isaks, J. Oliver, L.R. Sykes, W.J. Morgan, X. Le Pichon, J.R. Heirtzler, and many others.

The essence of this theory (V.E. Khain has propounded it at length in the USSR) is as follows. All of the earth's surface is divided into broad blocks, or plates of the earth's crust and upper mantle separated by the rift zones of mid-oceanic ridges. These ridges make up a system of welts of the earth's crust. The overwhelming majority of earthquake foci cluster along just these zones (Fig. 30) or are associated with Circum-Pacific island arcs and deep-sea trenches. In addition, the plates are composed of areas of both continents and ocean floors. All in all, there are seven or eight major plates and very few minor blocks on the earth's surface.

The plates move relatively to one another along the welts, are shoved against each other, or converge. They are rigid blocks of the crust and upper mantle, that is, of the lithosphere, which lie on the plastic asthenosphere. Currents in the asthenosphere displace the plates.

The blocks diverge at mid-oceanic ridges. As a result, a cleft (rift zone) forms, which is a passageway for the rise of asthenospheric material to the surface. This is accompanied by violent volcanism, seismicity of mid-oceanic ridges, and the greatest heat flow in the earth's crust.

During the divergence of the blocks at the rift zone, a new earth's crust forms and gradually grows outward from the median line of the rift zone. The result is the build-up and gradual extension of the crust.

The sea floor spreads along what are called transform faults at a right angle to the rift zone. These transform faults divide the broad oceanic plates into blocks which may differently slip relatively to each other.

Evidence for sea-floor spreading are the magnetic anomalies, which produce bands parallel to rift zones. These anomalies look like magnetic reversals alternating due to different times of their formation. The earth's magne-

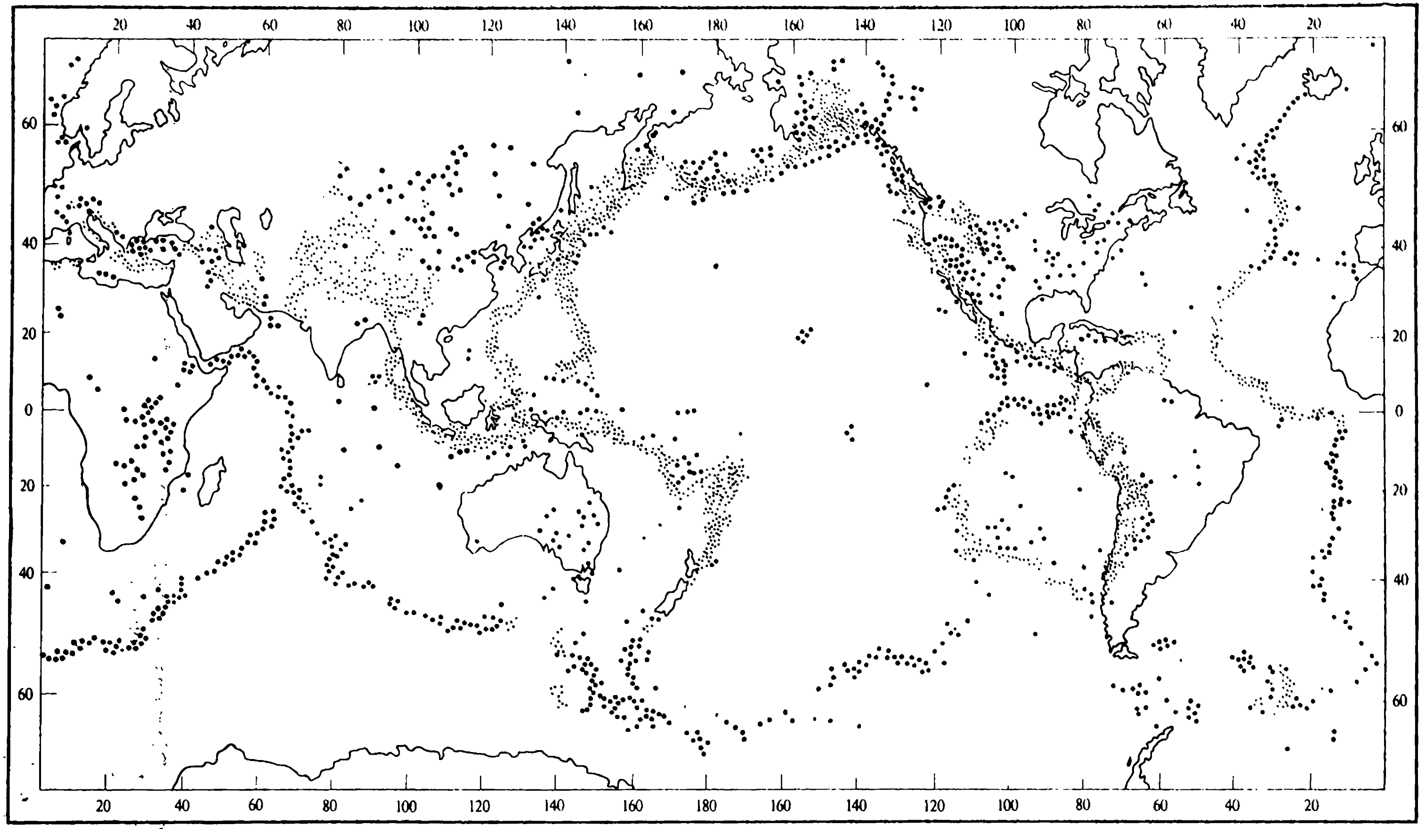


Fig. 36. Location map of major earthquake epicenters (dots) between 1961 and 1967 (after M. Barzangi and Dorman)

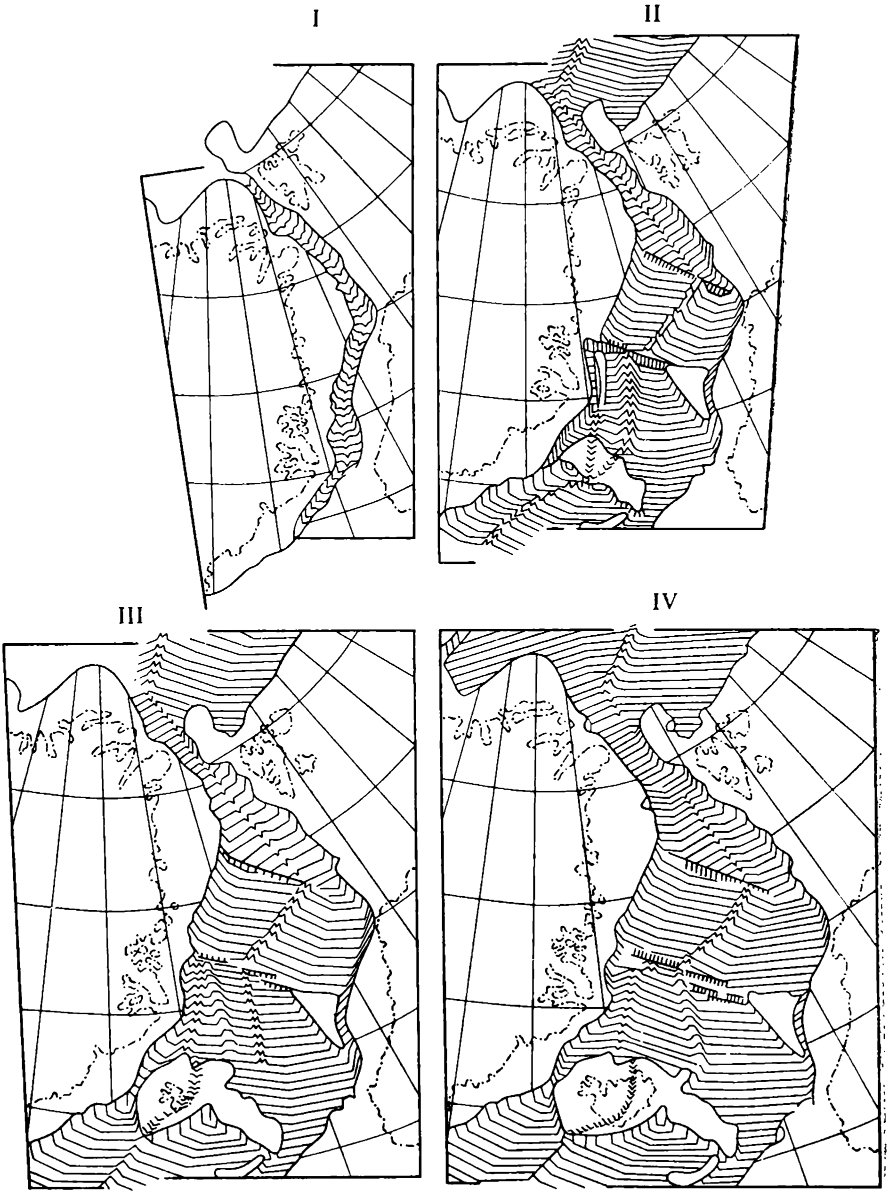
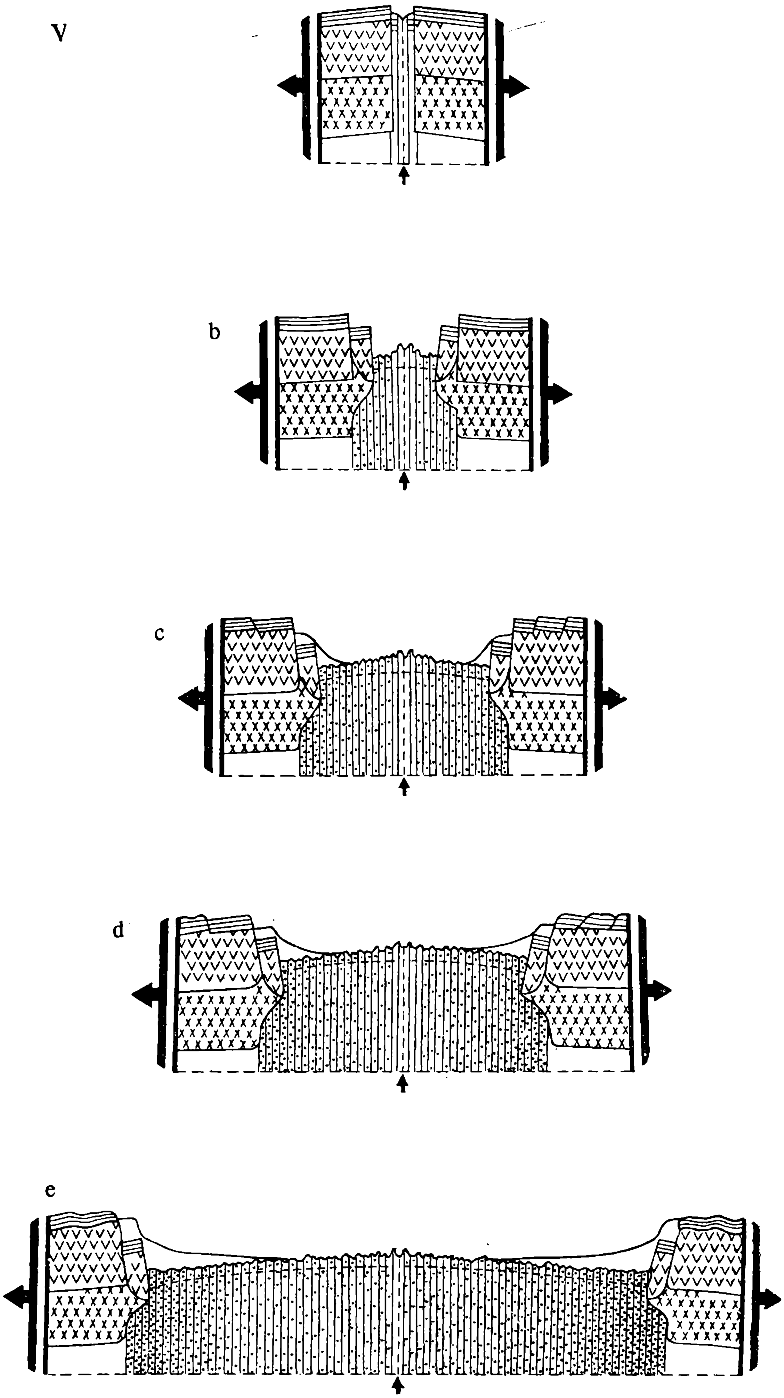


Fig. 37. **Diagrams representing the successive stages of Northern Atlantic floor spreading through the extension of the crust at the rift of the Mid-Atlantic Ridge (after B.C. Heezen, 1972):**

I through *IV* — successive stages of ocean-floor spreading;

V — same in cross sections; top diagram is graben in continental crust, as that beneath Red Sea; next, situation presents the Gulf of Aden; lower diagrams represent successive stages of Atlantic Ocean basin extension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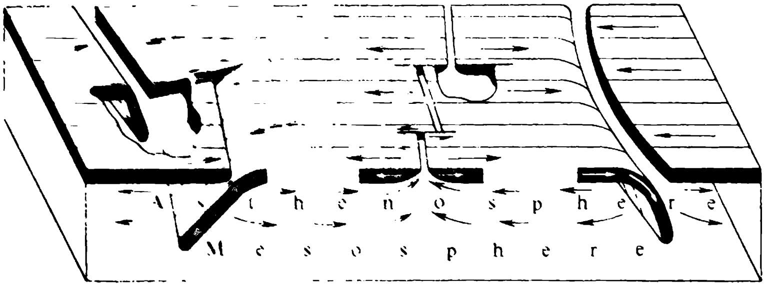


Fig. 38. Diagram of movements in the earth's crust, upper mantle and asthenosphere, and of subduction of the lithosphere beneath island arcs, such as the Tonga arc (after B. Isaks, J. Oliver, and L.R. Sykes, 1968)

tic field polarity changed while the crust was spreading at rift zones. The resulting magnetic reversals are fixed in the rocks thus indicating their different ages. In addition, the deep-sea drilling evidence obtained by the Research Ship *Glomar Challenger* in the Atlantic appears to confirm the different ages of the rocks overlying the basaltic layer within the ocean floor outward from the mid-oceanic ridge. Thus the sediments within its limits are of Neogene age. Farther from the ridge, the sediments are of Neogene and Paleogene age, then come Neogene, Paleogene, and underlying Cretaceous sediments, and, finally, Jurassic strata lie beneath the Cretaceous on the margins of the ocean. Older sediments were not found within the ocean (Fig. 37). Hence, the Atlantic Ocean seems to have originated in the Jurassic and gradually extended until Neogene and Quaternary times.

Some scientists (B. Isaks, J. Oliver, and L.R. Sykes, 1968) believe that the extension of the Pacific Ocean outward from its mid-oceanic ridge has generated deep-sea trenches at its edges. At these trenches, the oceanic crust, together with the uppermost mantle, slips along on oblique deep-seated faults under the Circum-Pacific continental blocks. It is precisely for this reason that Mid-Pacific basaltic volcanism is followed by andesitic volcanism on the ocean margins. The plunging of the oceanic crust under the continental crust has been termed "subduction" (Fig. 38).

However, no deep-sea trenches are present at the edges of other oceans, except for the Java Trench bounding the Indian Ocean on the northeast. That is why such a mechanism is difficult to explain from the geologist's point of view.

Many of the authors of the global tectonics hypothesis use it to explain all features of crustal structure and history. The hypothesis, however, does not deal whatsoever with geosynclinal cycles and the mode of formation of the continental crust. It can more or less thoroughly substantiate only the probable origin of ocean basins, particularly the gradual spreading of their floors, a point of keen interest.

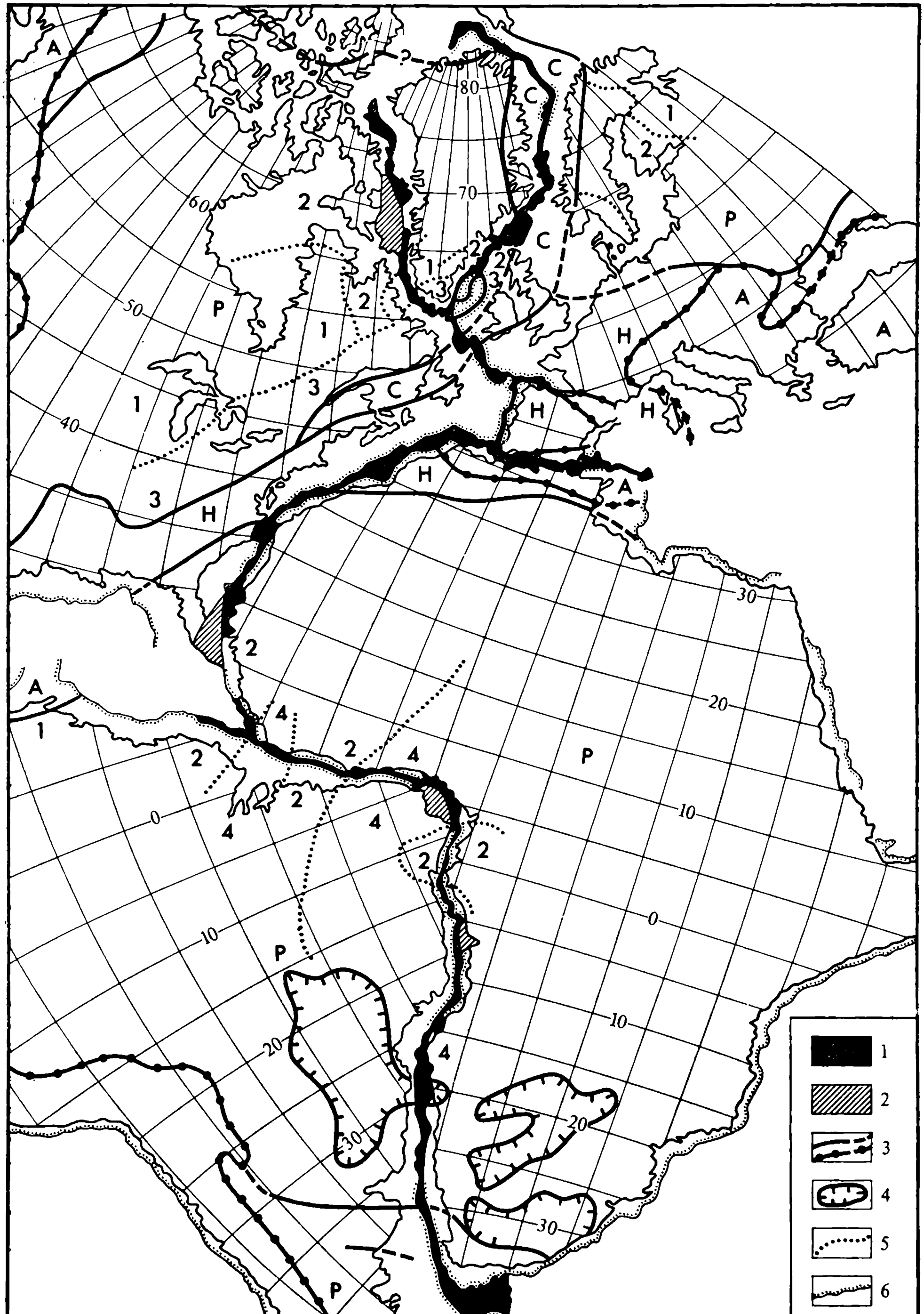
The relatively recent hypothesis that the diameter of the earth is growing presents a completely different explanation for ocean basins. It uses neither complex transformation of crustal composition nor the assumption of considerable lateral displacement of continents. Accordingly, it eliminates most objections to the above-mentioned hypotheses.

O. Hilgenberg, a German geodesist, first proposed this hypothesis in 1933. Three decades later he published several papers reconstructing the positions of the poles during Carboniferous to Eocene times on the basis of paleomagnetic data from more than 350 localities. Further, he determined a number of equatorial positions for the Carboniferous and Permian. From the geodetic data on the positions of the poles and equator, Hilgenberg concluded that the diameter of the earth in Carboniferous time constituted 69 percent, and in Permian time 72 percent of today's diameter. In the Carboniferous, therefore, the area of the earth's surface was less than half its present area (213 million square kilometers and 510 million square kilometers, respectively). From these data, he has constructed several globes showing continental masses and oceanic expanses. He has concluded that two continental masses existed during the Carboniferous and Permian: one combined Europe, Africa, and America and other Australia and Antarctica. After the Permian, the diameter of the earth was found by interpolation, and a number of stages were distinguished in which the earth's surface progressively expanded in Triassic, Jurassic, Cretaceous, and Eocene times at the expense of oceans. The increase in the earth's surface was accompanied by the broadening of the ocean floors and the formation of new ocean basins. As a result, the blocks of the continental crust were separated by the oceanic crust and gradually moved away. The expanding earth hypothesis considers the continental crust to be ancient, generated at a much shorter diameter of the earth while the oceanic crust is regarded as formed by the expansion of the earth's surface.

I.V. Kirillov put forward this hypothesis independently of Hilgenberg at a meeting of the Moscow Naturalists Society in 1957. Using several paleogeographic globes with different diameters for different geologic periods, which were constructed on a purely empirical basis, he demonstrated the arrangement of continents and oceans. Despite some errors in presenting paleogeographic facts, the attempt was interesting. V.B. Neumann later published a paper (1962) supporting this concept.

The weakest point of the expanding earth hypothesis is the lack of a cause for this process. Hence it is completely devoid of a theoretical basis. True, according to general considerations, the core of the earth consists of the metallized supercompact material which is spontaneously transformed into a less dense material with a corresponding expansion. However, these considerations are purely speculative.

At the same time, this hypothesis accounts for many geologic facts without serious objections. Three basic structural and historical divisions can be distinguished in the earth's crust: the crust of ancient platforms, the thickest of the stable sections of the earth's crust; the crust of fold belts, including the crust of young platforms, thinner than that of ancient platforms,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and the more complex crust of the contemporary geosynclinal areas; and the oceanic crust.

These divisions can be considered to represent three successive stages of the earth history with three diameters: ancient platforms are remnants of the oldest crust which covered a small globe, fold belts are remnants of a much larger globe, and the oceanic crust is related to the newest history of the earth and the latest stage of its expansion.

Therefore, the expanding earth hypothesis is largely in accord with geologic evidence and at any rate does not contradict the data on the history of the earth's surface.

THE PROBABLE AGE AND THE MODE OF FORMATION OF OCEAN BASINS

Nobody can definitely explain the origin of the ocean basins. Judging from the above-mentioned data on the geology of ocean coasts and floors, ocean basins differ in origin and age.

The geologic data on the continents and the relationship between their coasts and the ocean basins clearly suggest the existence of two types of ocean basins on the earth's surface, such as the Pacific basin, whose floor is the most ancient thalassocraton, and the secondary, newly formed Atlantic basin, which originated at the site of previous continental masses.

Although the Pacific basin can on the whole be considered primary, we cannot rule out the possibility that some of its areas, particularly those related to and adjoining the Mid-Pacific Ridge, are much younger.

The basins of the Atlantic, Indian, and Arctic Oceans are younger with the basin of the Indian Ocean being the oldest, supposedly of Paleozoic age. According to the above-mentioned paleomagnetic and drilling evidence, the Atlantic Ocean probably formed in the Triassic, the early stage of its formation taking place in the Jurassic. The Arctic Ocean is even younger, apparently of Cretaceous or Paleogene age. Ocean basins may very likely differ in origin, as follows from the information on their structure.

Notably, Wegener's suggestion that the coast lines on both sides of the Atlantic fit each other was not only confirmed but also specified. The matching proves to be even more striking if we correlate the continental slopes rather than the coast lines. E.C. Bullard, a British geophysicist, has published a map showing the matching results for the Atlantic coasts in a projection that does not distort the present continental slope contours (Fig. 39). Similar data have been presented by P.N. Kropotkin.

◀ *Fig. 39.* Coasts of Africa, Europe, and America fitted together by their continental slopes (580-m isobath), without distortion of their size and form (after E. Bullard):

1 — ocean floor between continents;
2 — continents overlapping;
3 — boundaries of fold areas and platforms;
4 — major basin;
5 — trend of Precambrian structure;
6 — continental rise

Letters on map:
P — ancient and epi-Baikalian platforms;
H — Hercynian fold areas;
C — Caledonian fold areas;
A — Alpine fold areas

Evidence is available for the compaction, or basification, of the earth's crust beneath the Indian and Arctic Oceans, as is suggested by broad areas of continental crust which are remnants of the granitic-metamorphic layer.

The sea-floor spreading hypothesis, based on the processes operating in mid-oceanic ridges, explains many geological and geophysical aspects of their structure. Hence it can be partially recognized as shedding light on the origin of secondary ocean basins. It cannot be accepted, however, as a universal theory of the earth's development, as many geophysicists and geologists outside the USSR consider.

At the same time, the basic conclusions of this hypothesis can be easily accounted for by the expanding earth hypothesis. The worldwide system of mid-oceanic ridges can be visualized in terms of this hypothesis as a system of scars along which the earth is expanding. No wonder many outstanding scientists who have studied the geology of the ocean floor (R.W. Fairbridge, B. Heezen, and others) support this concept.

X

MAJOR HISTORICAL EVENTS AND THE STAGES OF FORMATION OF THE EARTH'S CRUST

Having familiarized ourselves with the structure and history of the continental and oceanic crust, we can try to broadly outline the major stages of its development responsible for the present-day face of the earth.

The earth's crust is known to consist of units of different structure and ages. Their successive formation allows us to present a general picture of crustal development.

The most ancient unit of the earth's crust is the basaltic layer beneath the continents and probably the Pacific floor. The basement of ancient platforms is next in time, and then follows the basement of major and minor fold belts, that is, young platforms stabilized by the end of the Paleozoic.

The youngest units of the crust are fold areas consolidated in the Mesozoic and Cenozoic, the floor of secondary oceans, the Indian, Atlantic, and Arctic, and the present geosynclinal areas of the Circum-Pacific and Mediterranean belts. These last include the young basins of inland seas, the Mediterranean, Black, Japan, Bering, and others.

Five major stages are recognized in the history of the crust by the ages of its units.

First comes the stage of the earliest existence of the earth, before the earth's crust had originated, when the earth was a luminous body. The second stage covers the origin and early existence of the basaltic crust. The third stage marks the formation of the basement of ancient platforms representing the most ancient continental crust. The fourth stage consists in the stabilization of the broad expanses of fold belts and is of Riphean through Paleozoic age. In this stage, broad areas of the Mediterranean and Circum-Pacific belts were stabilized to young platforms. The fifth stage encompasses the general shaping of the contemporary continents and the appearance of the

intervening secondary basins of oceans and inland seas until the existing relationships among the continents, seas, and oceans formed and the present topography created.

THE EARLY EXISTENCE OF THE EARTH BEFORE CRUST FORMATION

We know now that the sun and the planets of the solar system are probably 5 000-7 000 million years old, as determined from dates of 4 500-5 000 million years obtained for meteorites falling on the earth's surface. Meteorites appear to be fragments of a planet earlier included in the solar system and then disintegrated. It is presently thought that all the planets of the solar system formed at the same time as the sun; hence, the age of meteorites determines the age of the whole system.

Early in its development, the earth was not yet covered by a crust. According to early concepts, our planet was first a luminous, then an incandescent solid body which gradually cooled by radiating energy into space. In more recent views, the earth and other planets of the solar system originated by the condensation of cold solid particles, similar in composition to meteorites, and gases. According to O.Yu. Schmidt, V.G. Fesenkov (1960, 1964), and other astronomers, these particles formed what Fesenkov called a globule, a gas-condensed dust nebula. Condensation and compaction of the central part of the cloud generated the sun while its outer parts formed the planets. Gradually getting together into a more and more compact body, primary particles condensed into a protoplanet. In becoming more compact, the primary planet must have been heated until it completely melted. It was only since then that a crust has begun to form on its surface.

The early stage was rather protracted. According to the data now available, the most ancient parts of the earth's crust are estimated at more than 4 500-5 000 million years old. But we cannot say now when it was initiated. Given the above-mentioned data on the age of the earth, the early period of earth existence before the crust formation lasted nearly 1 000 million years.

THE BASALTIC CRUST BEFORE HYDROSPHERE FORMATION

For a long time the earth's crust was a very thin and weak shell, easily molten and broken up.

During the early evolution of the earth's crust, tremendous volcanic phenomena were active. Seas of lavas poured out on to the earth's surface through fissures and faults from under the extremely incompetent crust. Uprising volcanic materials simply melted through the broad areas of the earth's crust. Later, when the crust became somewhat thicker and harder, volcanic processes, still very violent, were restricted to fault zones cutting through the crust and manifested themselves as fissure outpourings, lofty volcanic cones, and explosion craters. As early as 1922, Professor A.P. Pavlov, the

famous Soviet geologist, called this early phase in the history of the earth's crust "lunar". Indeed, the lunar surface now exhibits the "frozen" traces of enormous volcanic phenomena: an infinite number of volcanic cones, explosion craters, huge lava fields, outpouring fissures, and other features.

The lunar phase resulted in the generation of the melanocratic part of the earth's crust composed of basic (basalt, gabbro, and other rocks) and ultrabasic igneous rocks. All of them lie at the base of the present crust, constituting the geophysically detected basaltic layer of the continental crust. Perhaps it previously covered all of the earth's surface forming a crust similar to the modern oceanic crust. We cannot consider, however, that all of the latter originated early in the earth's life. Rather, the evidence available suggests that broad areas of the oceanic crust are newly formed. It is only the Pacific that may be largely underlain by the most ancient crust, though it has, of course, undergone further changes.

The oldest melanocratic crust was later buried under the granitic-metamorphic layer of the continental crust.

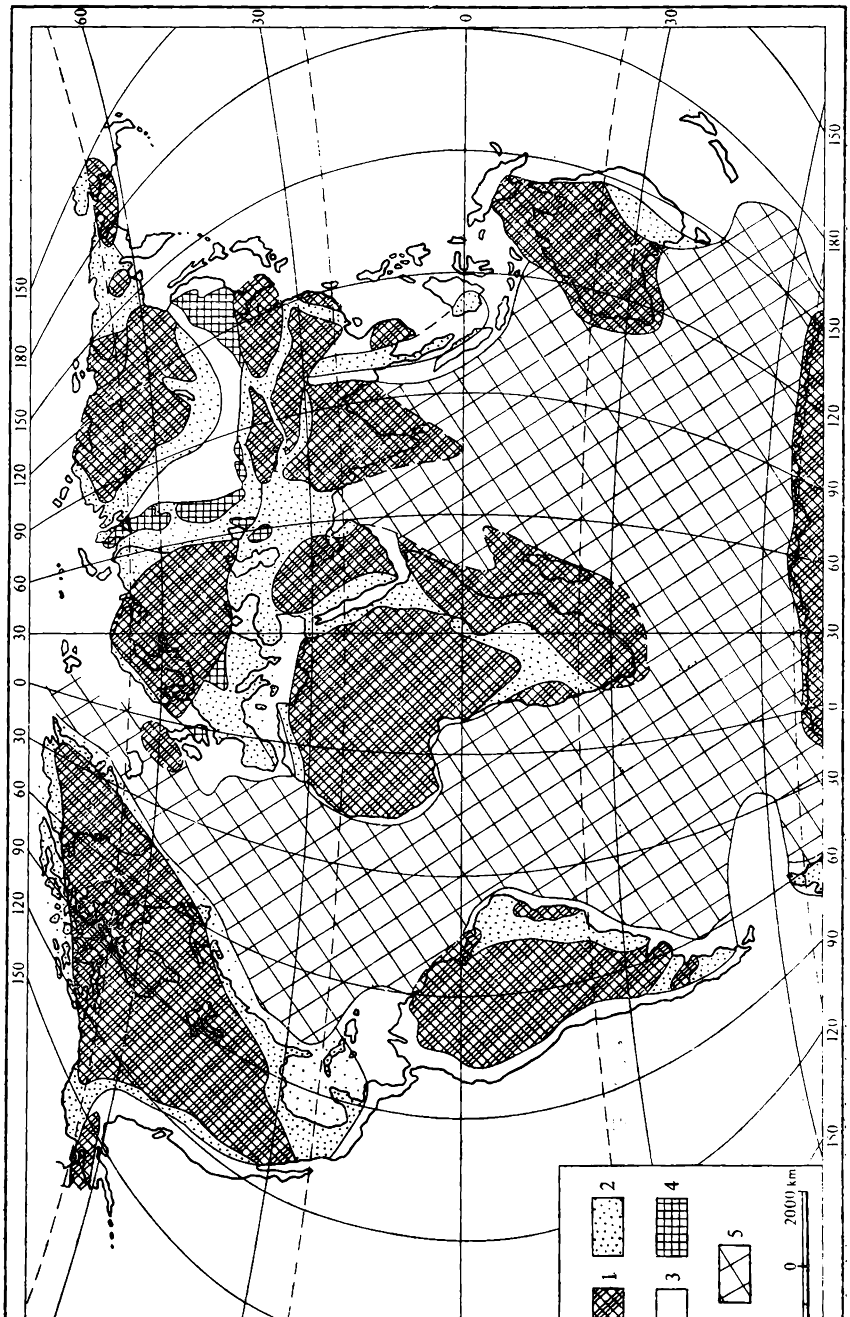
On the moon, which has no atmosphere, the basaltic layer has preserved its original make-up produced by volcanic activity, although it has been disturbed by various deformations and meteorite impacts. The lunar surface reflects, therefore, the early stage in the evolution of the crust that our planet also passed through, but whose traces on the earth are completely absent.

A primary atmosphere was undoubtedly present during the lunar phase of the earth's development. It differed drastically, however, from the present, nitrogen-oxygen atmosphere, which appeared much later. The primary atmosphere consisted of gases evolved by volcanic eruptions, such as steam, methane, carbon dioxide, ammonia, nitrogen, and hydrogen with an admixture of inert gases (He, Ar, Xe, and Kr), and what are called acid fumes escaped from volcanoes [HCl, HF, H_3BO_3 (boric acid), H_2S, and others]. A.P. Vinogradov, N.M. Strakhov, and A.B. Ronov treat the chemical composition of the atmosphere, and the history and origin of its individual components.

Since then the primary atmosphere has changed greatly. Thus, hydrogen and some helium, which are light gases, have dissipated while oxygen has been introduced to play an increasing part in the origin and development of life on earth. The lunar phase was probably short-term and lasted until the surface of the primary crust and the lower atmosphere cooled down below +100 °C, in other words, until liquid water covered the lowermost areas of the primary crust. As a result, ancient seas, lakes, and streams formed. Then intense processes began to erode the ancient crust, weather its surface, and transport debris by streams and deposit it on the bottoms of water bodies, where it alternated with volcanic tuffs and lavas.

These processes started to erase the traces of the most ancient lunar phase. The face of the earth was being shaped by a combination of both internal forces, which upheave, bend, and break up the earth's crust and make volcanoes erupt, and external forces, which destroy the results of internal processes and cover the crustal surface by sediment.

Therefore, the early, pre-Archean era of crustal history is rather clearly delineated. A primary crust, which now represents the basaltic layer beneath the ancient platforms and Pacific Ocean, was generated at the beginning and a water layer blanketed its surface at the end.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THE FORMATION OF THE GRANITIC-METAMORPHIC CRUST OF ANCIENT PLATFORMS

The next stage in the evolution of the earth's crust marked the formation of the basement of ancient platforms and lasted throughout the Archean and the first half of the Proterozoic (until the Riphean), that is, for more than 2 000 million years (from 3 800 to 1 600 million years ago). This very protracted stage can be subdivided into three successive phases.

The first phase encompassed the period when the earth had no continental crust and geosynclines and platforms, but had primary oceans and land. The most ancient crust was similar in structure to the present-day oceanic crust; it comprised the basaltic layer covered by a thin layer of sediment.

This phase was not only pre-geosynclinal, as many scientists admit, but also pre-continental, lacking great masses of the acid rocks now making up the continents.

A.A. Borisyak wrote about the pre-geosynclinal phase of crustal history. E.V. Pavlovsky and M.S. Markov (1962) described this phase in detail and called it the nuclear phase. J. Gill and J.T. Wilson also mentioned the features of the early phase, and Wilson attributed it to the formation of the greenstone nuclei of continents. E.M. Laz'ko (1971) and V.E. Khain (1963), like many other scientists, name it the pre-geosynclinal stage.

At the beginning of the Archean, sedimentation and volcanism occurred on the floors of the oceans which covered the primary crust.

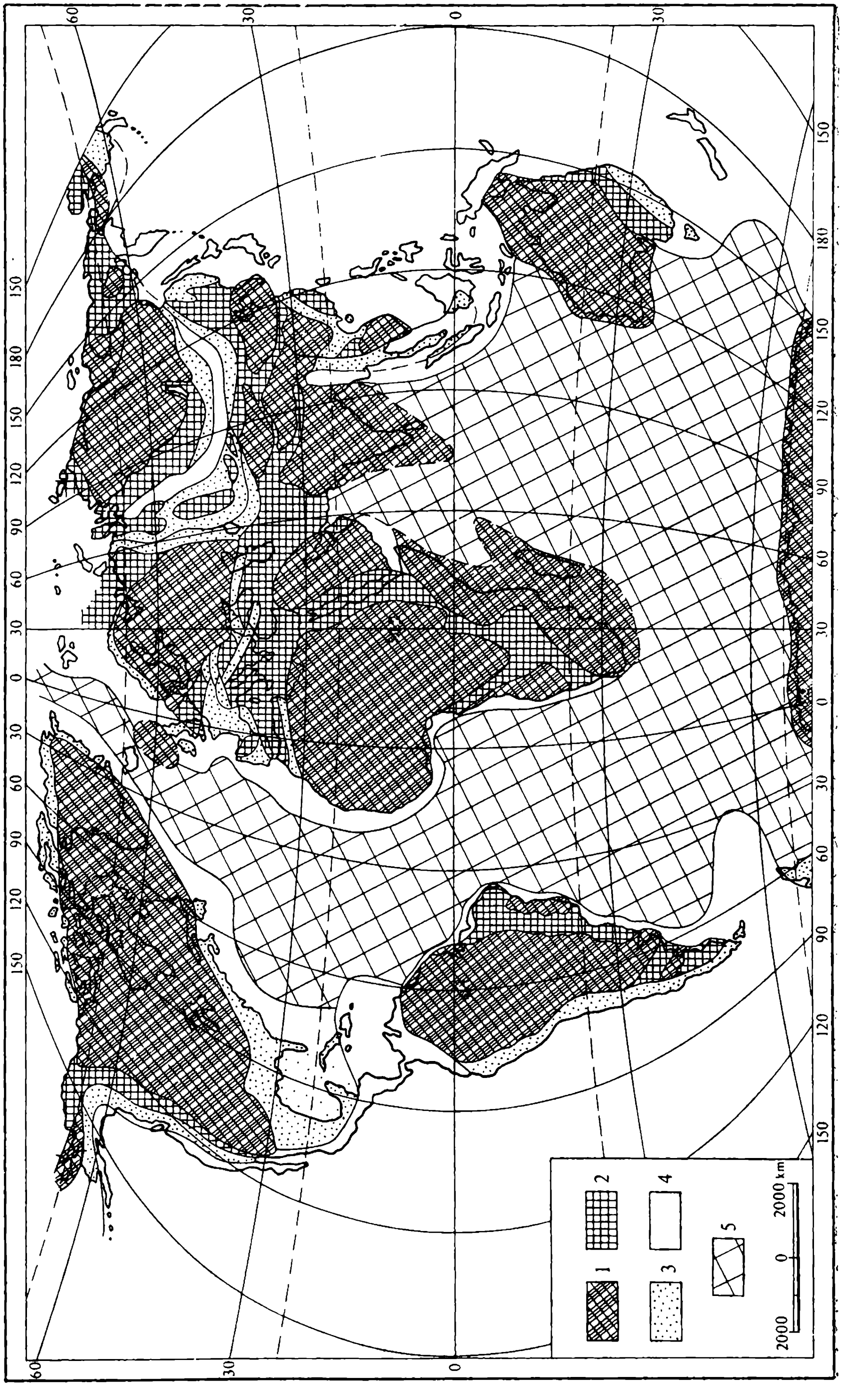
N.M. Strakhov (1963) stressed that the composition of the atmosphere, water medium, and sediments derived from redeposition of minerals of volcanic rocks and weathering products in a nearly oxygen-free atmosphere had been completely different at the beginning of the Archean. That time was marked by the laying-down of basic lavas and tuffs, alumina (Al_2O_3)-rich clayey-sandy rocks, and chemical ferruginous-siliceous sediments. They were metamorphosed to amphibolite and gneiss complexes of basic composition, which are well known to make up the most ancient portions of the basement of all ancient platforms. They are observed in some places to immediately overlie the basic rocks that compose the crustal basaltic layer.

In the second phase, thick sedimentary and volcanic series filled large troughs termed protogeosynclines. These sediments then were folded and metamorphosed with extensive granitization and the origin of granitic magma and granite-gneiss domes.

In the third phase, actual geosynclinal trough systems and an early sedimentary (protosedimentary) cover of Archean massifs began to form since early Proterozoic time.

Fig. 40. **Paleotectonic map showing the earth's surface just before the Riphean:**

1 — ancient platforms underlain by continental crust;
2 — geosynclinal areas of oceanic fold belts having oceanic- and transition-type crust;
3 — regions of oceanic crust;
4 — principal platform-type masses formed at the beginning of the Riphean;
5 — present-day seas and oceans absent at the end of the Proterozoic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Within the Proterozoic geosynclinal systems, processes of folding and granitization generated a thick granitic-metamorphic basement, which welded together, as it were, separate Archean massifs. The result was the massive foundation layer of ancient platforms (Fig. 40).

Subsequently, the basement was further transformed. It underwent repeated extensive granitization and metamorphism, mainly at the margins of the ancient platforms. Moreover, during the protracted deposition of the sedimentary cover, the basement was faulted and deformed.

THE CONSOLIDATON OF THE BASEMENT OF YOUNG PLATFORMS

The next major stage in the evolution of the earth's crust was the development of fold belts between ancient platforms and their stabilization to produce young platforms. This stage spanned more than 1 300 million years (between 1 600 and 240 million years ago).

At the outset, a melanocratic oceanic crust existed in the areas later occupied by fold belts. After the beginning or middle of the Proterozoic, a geosynclinal cycle began to develop in some of their regions. The belts of the oceanic crust were either remnants of the most ancient melanocratic crust preserved between ancient platforms after the origin of their granitic-metamorphic layer, or were newly formed by the divergence of continental blocks.

The geosynclinal areas of that period had an oceanic crust. Throughout the middle Proterozoic and Riphean, the processes within these areas generated extensive belts of the granitic-metamorphic layer. Thus by the end of the Riphean all of the minor Intra-African and Brazilian fold belts had been underlain by the granitic-metamorphic layer and hence converted into the basement of young platforms (Fig. 41).

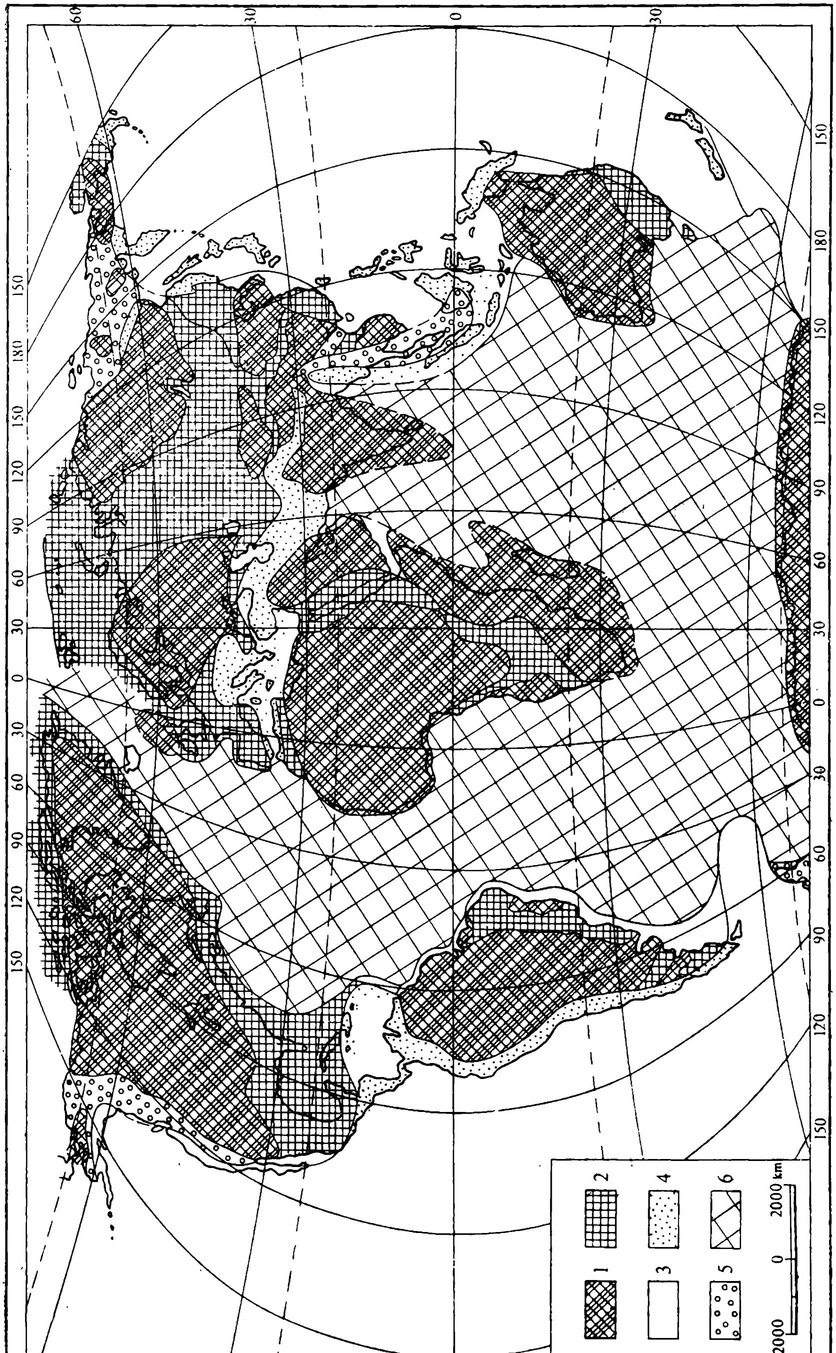
At that time, the major belts were also largely underlain by continental crust, but still contained "windows" of the ancient oceanic crust. Thus, within the Circum-Pacific belt, the continental crust formed during Riphean time only in relatively limited areas on its margins.

In the Paleozoic, the continental crust continued to build up within major belts. At the same time, many Paleozoic geosynclinal areas were initiated in the earlier formed but broken granitic-metamorphic layer.

Over a long period, huge expanses of fold belts were stabilized, except for the almost entire Circum-Pacific belt and part of the Mediterranean belt. Only the marginal part of the Circum-Pacific belt and mainly the western part of the Mediterranean belt became underlain by the granitic-metamor-

Fig. 41. Paleotectonic map showing the earth's surface at the end of the Paleozoic:

Area underlain by continental crust:
1 — ancient platforms;
2 — young platforms;
3 — geosynclinal areas;
4 — areas underlain by oceanic crust and Atlantic continental shelf;
5 — areas of oceans absent in Paleozoic time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phic layer. Therefore, by the end of the Paleozoic the Atlantic, Ural-Mongolia, and Arctic belts, as well as the western Mediterranean belt, had been converted into the basement of young platforms. The resulting broad massifs of the continental crust consist mainly of ancient and young platforms. At the same time, major tectonic elements formed on the ancient platforms: aulacogens (intracratonic troughs), pericratonic troughs, syneclises, shields and anteclises (arched uplifts), and major and minor faults and flexures.

THE LATEST STAGE IN THE DEVELOPMENT OF THE EARTH'S CRUST

The Mesozoic-Cenozoic stage of the earth's history is relatively short, its duration is only 250-240 million years. Its basic feature is the platform-type development of the newer continents consisting of both ancient and young platforms. Their extensive depressions and uplifts continued to develop, and fault systems formed giving rise to volcanic activity (Fig. 42).

At the same time, much importance should be attached to the orogenesis involving extensive areas of young and, to a lesser extent, ancient platforms. As a result, numerous mountain areas and long ranges rose. Two great systems of rift valleys also appeared: the African rifts and the grabens of Lake Baikal, with the accompanying upheavel of mountain ranges and volcanic activity.

Along with these processes, the surface of continents, their mountains and plains, were affected by weathering, erosion, glaciation, and other processes especially active in uplifted areas, on the one hand, and by the accumulation of sediment in subsided depressions and plains, on the other. Hence this stage can quite rightly be characterized as forming the topography and, in general, the modern shape of continents (Fig. 43).

This stage also witnessed the formation of the broad secondary Atlantic, Indian, and Arctic basins. Whatever their origin, the huge protocontinent of Gondwana disintegrated and Africa, Australia, South America, Antarctica, and the far-distant platform of the Hindustan Peninsula became separated by secondary ocean basins.

This stage also included the generation and development of young geosynclinal areas—the Alpine and Indonesian in the Mediterranean belt, and the innermost Circum-Pacific belt—which have only partially completed their geosynclinal cycle.

During the same stage, the numerous basins of inland seas in the Mediterranean belt and of the marginal seas fringing the Pacific Ocean sunk and became restricted to the contemporary geosynclinal areas.

Fig. 42. Paleotectonic map showing the earth's surface in the Mesozoic:

Areas underlain by continental crust:
1 — ancient platforms;
2 — young platforms;
3 — areas of oceanic crust;
4 — geosynclinal areas;
5 — geosynclinal areas in orogenic stage;
6 — younger ocean floor

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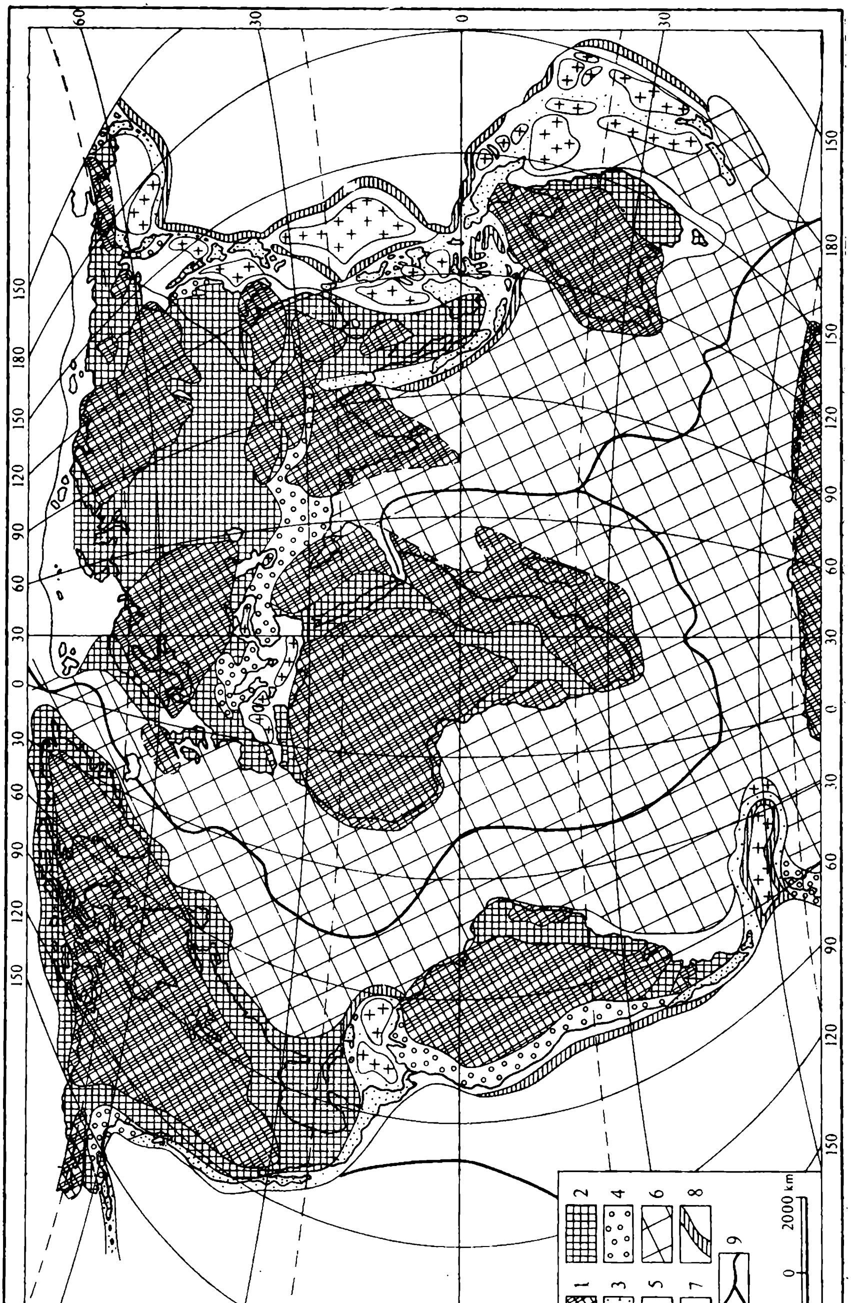
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THE GENERAL TREND IN THE DEVELOPMENT OF THE EARTH'S CRUST

After the formation of the basaltic layer of the earth's crust, the succeeding events gradually enlarged the extension and volume of the granitic-metamorphic layer. This means that the continental crust formed and grew.

The continental crust had grown to a maximum by the end of the Paleozoic, after the consolidation of the basement of young platforms. From about that time, the huge continental masses began to split up and secondary ocean basins began to appear. The hypotheses of continental displacement, sea-floor spreading, and earth expansion do not require to their advantage the transformation of the continental crust back into the oceanic crust. They regard the development of the earth's crust as a positive process toward the build-up of continental crust. The basification and compaction hypotheses imply, as mentioned earlier, an unavoidable conversion of the granitic-metamorphic layer into a denser material physically corresponding to the basaltic layer of the crust and to the uppermost mantle. This probably means that the mineral associations present in the interior of the crust would pass into a denser metamorphic facies under the action of increasing pressure and temperature. This process, however, is difficult to assume for such broad basins as the Atlantic, Indian, and Arctic basins, though it can most likely explain the origin of the extensive but gentle-sided syneclises on both ancient and young platforms. This hypothesis so far gives the most satisfactory account of the origin of the Mediterranean, Black, and other inland and marginal sea basins. Hence we cannot reject the possible importance of this process in the generation of major basins on the earth's surface. The problem is only the extent of this process, which appears to be too large in case of ocean basins.

In addition, the striking similarity between the coastlines of Africa and America is always a matter of contemplation, because while it cannot be accounted for by simple coincidence, it can be explained by assuming the rupture of these coasts when Gondwana disintegrated.

With this in mind, we cannot consider that the only process of the earth's crust development was the single build-up of the granitic-metamorphic layer. The history of the crust is very complex and protracted, and we are only beginning to study and understand it.

Although the build-up of the continental crust is undoubtedly of the utmost importance, its transformation into a denser material and hence the generation of different depressions of the earth's surface is also important.

Fig. 43. Paleotectonic map showing the earth's surface in the Cenozoic:

Areas underlain by continental crust:
1 — ancient platforms;
2 — young platforms;
3 — geosynclinal areas of Mediterranean and Circum-Pacific belts;
4 — Cenozoic fold areas in orogenic stage

Areas underlain by oceanic crust:
5 — Pacific;
6 — younger oceans (Atlantic, Indian, and Arctic);
7 — floor of inland and marginal seas;
8 — major deep-sea trenches;
9 — system of mid-oceanic ridges

Modern evidence also suggests the probable lateral divergence of crustal blocks of the continental crust, which easily explains the appearance of such basins as the Red Sea graben and the Atlantic floor.

These and many other aspects of the geology and history of the earth's surface are in good agreement with the expanding earth hypothesis. We can visualize that the crust of ancient platforms formed at a much shorter diameter of the earth, that fold belts developed at a longer diameter, and that newer oceans widened during the third stage of the earth's expansion. Therefore, the geological evidence favors the further elaboration of this hypothesis, although just how the earth physically expands is still uncertain.

Along with basic processes of generation and development of the earth's crust, the earth's surface, or the face of the earth, has been continuously evolving. This has determined land and sea configuration, distribution of water bodies on the earth's surface, and, to some extent, atmospheric circulation. The surface of the continental crust and the ocean water are the habitat of man and other organisms. The formation of the earth's crust resembles the long-term construction of a house occupied by a succession of generations of inhabitants.

The boundaries between stages are very important in the history of the earth's crust, since they mark major epochs of folding, emplacement of granitic intrusions, metamorphism, and granitization. Mention should first be made of the epoch after the formation of the basaltic layer at the beginning of the Archean; then that at the end of the middle Proterozoic and the beginning of the Riphean; and, finally, that at the end of the Paleozoic (Hercynian folding).

Those epochs of folding and granitization that occurred in the middle of the Archean, at the boundary between the Archean and Proterozoic, and in the middle and at the end of the Riphean are also important.

The folding epochs are often considered not only the boundaries, but also active periods between the almost inactive periods of oscillatory movements. They are all tectonic cycles repeating throughout the earth's history. Folding epochs, or tectonic cycles are considered "spasms" involving all of the earth's surface and crumpling sedimentary and metamorphic series into folds. In fact, however, geosynclinal processes in their entirety play the leading role in the build-up of the continental crust at least after the Archean. They are responsible for thick series of volcanic and sedimentary rocks, their repeating folding, and the complex evolution of magmatic materials with their transformation into a wide range of plutonic and volcanic rocks of different composition later metamorphosed and granitized. The end of the geosynclinal cycle is always a major boundary. However, the granitic-metamorphic layer builds up not only during a folding epoch, but also as a result of the entire protracted development of a geosynclinal area.

Returning to the analogy of building a house, the stages are the construction of the basement and each storey. Similarly, the components of the earth's crust are created during successive stages, each having a different extent and duration and separated by definite boundaries.

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